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REDUCTION OF ATMOSPHERIC POLLUTION

FINAL REPORT ON RESEARCH ON REDUCING EMISSION OF SULPHUR OXIDES, NITROGEN OXIDES, AND PARTICULATES BY USING FLUIDISED COMBUSTION OF COAL

Appendices: (Vol. 2 of 3)
1 -- Experiments with 36-in. combustor
2 -- Experiments with 48 x 24-in.
    pressurized combustor
3 -- Experiments with 27-in. combustor

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Three appendices to the main report on research on reducing emission of sulphur oxides, nitrogen oxides, and particulates by using fluidised combustion of coal are presented. They are: Experiments with 36-in. combustor; Experiments with 48 x 24-in. pressurized combustor; and Experiments with 27-in. combustor. Descriptions of the plant, operating procedures, and results are included in each.

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FINAL REPORT

JUNE 1970 - JUNE 1971

REDUCTION OF ATMOSPHERIC POLLUTION

APPENDIX 1. EXPERIMENTS WITH THE 36 IN COMBUSTOR. (TASK I)

PREPARED FOR

ENVIRONMENTAL PROTECTION AGENCY
OFFICE OF AIR PROGRAMS
411 WEST CHAPEL HILL STREET
DURHAM, NORTH CAROLINA 27701

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FLUIDISED COMBUSTION
CONTROL GROUP

NATIONAL COAL BOARD
LONDON, ENGLAND

REDUCTION OF ATMOSPHERIC POLLUTION

Research on reducing emission of sulphur oxides, nitrogen oxides and particulates by using fluidised bed combustion of coal

Appendix 1. Experiments with the 36 in combustor. (Task I)

Main objective

To compare the performance of the 36 in combustor with that of the 6 in combustors at the N.C.B's Coal Research Establishment and at the Argonne National Laboratory, and to extend the range of operating conditions for which experimental data is available.

Report prepared by: D.G. Cox and J. Highley

Report approved by: A.D. Dainton and H.R. Hoy

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FOREWORD

This Appendix describes experimental work carried out using the 36 in combustor at CRE., between June 1970 and June 1971, as Task I of the joint N.C.B./O.A.P. research programme. The objective of Task I was to compare the performance of the 36 in combustor with that of the 6 in combustors at CRE and Argonne, and to extend the range of operating conditions for which experimental data is available. Attention is drawn to the main results obtained, but the results are not discussed here. A summary of the work is presented in the main report and the results are discussed there, together with results from other pilot plants.

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(Note that when referring to Tables and Figures in the text the prefix A.1 is omitted).

1. DESCRIPTION OF PLANT

A general flow diagram of the 36 in combustor plant is given in Fig. 1.

1.1 The combustor

The design and dimensions of the combustor are shown in Fig. 2. The combustor comprised a mild steel shell, 4 ft 6 in square cross-section, fabricated in five sections. The combustor was supported at the centre section in order to permit the upper or lower sections to be removed for maintenance or modification. The upper four sections were refractory lined to give an internal cross-section of 36 in by 18 in. (The cross-section was originally 36 in square, but was reduced to allow operation at higher velocities with the existing air supply and cooling system).

The first section contained a stainless steel plenum chamber, 36 in square cross-section, 33 in high, to which the air distributor was bolted, Fig. 2. The plenum chamber was surrounded by loose fill insulation. A 3 in diameter bed ash offtake pipe passed down through the centre of the plenum chamber and terminated in a rotary valve.

The air distributor comprised a mild steel plate with 72 stand pipes on a 3 in square pitch in the central 36 in by 18 in area. The stand pipes were ½ in outside diameter stainless steel, 3½ in. long, and having four 0.147 in diameter holes drilled horizontally 3 in above the base plate. The distributor was designed to give a pressure drop of 10 in water gauge at a fluidising velocity of 4 ft/s, i.e. about 50% of the pressure drop of a 2 ft deep bed.

The second section, the boiler, contained the fluidised bed, the coal and additive feed lines, the fines recycle line and the cooling tubes. The coal and additive were fed through adjacent 1 in inside diameter pipes extending 7 in into the bed such that the feed could be considered as at the centre. The height from the air jets to the feed lines was 5 in. Preliminary tests in the 12 in corrosion rig, Task IV had demonstrated that coking of Pittsburgh coal could occur in the bed section of the coal feed line if this was uncooled. In order to prevent this occurring, a water jacketed coal feed line was used. The primary fines were recycled via a 3 in diameter line which entered the boiler section opposite the feed lines and extended 3/4 in into the bed. The boiler section usually contained a bed ash sampling probe, 6 thermocouples and 3 pressure probes arranged as in Fig. 3.

There were 14 cooling tubes installed in the boiler section, arranged on a 4½ in triangular pitch as shown in Fig. 2. The tubes were 2 in inside diameter, 2⅜ in outside diameter stainless steel and were sealed at one end, with an inner 1 in inside diameter tube. This design allowed all the associated pipework to be on one face of the combustor. The tubes were connected in series.

The two sections above the support section contained gas sampling points, thermocouples, pressure probes and steam injection lines, as shown in Fig. 3. The gas offtake was a 12 in diameter pipe from the top of the reactor. There were also two bursting discs for explosion relief in the top section. Fresh bed material was fed pneumatically to a point in the fourth section.

The total height from the distributor air jets to the gas offtake was 15 ft.

1.2 The fluidising air supply

The arrangement of the air supply is shown in Fig. 1. Air was taken from the 100 lb/in^{2}g mains supply and the pressure reduced to 45 lb/in^{2}g for flow measurement. In normal operation, without the hot gas generator, the total flow rate of air to the combustor was measured and then the coal and additive transport air were diverted from the fluidising air. For start-up there was an additional primary air line to the hot gas generator and part of the main air supply was fed to the generator as secondary air.

1.3 The cyclones and fines recycle system

The off-gas from the combustor passed through lagged 12 in diameter ducts to the primary and secondary cyclones and then to the stack. The primary cyclone was manufactured from stainless steel and was 24 in in diameter and 8 ft 10 in high. The gas inlet velocity was 37-75 ft/s at 4-8 ft/s fluidising velocity and the collection efficiency is shown in Fig. 4. The secondary cyclone, also of stainless steel was 17¼ in in diameter and 6 ft 7 in high and had a gas inlet velocity of 75-150 ft/s. The collection efficiency is also shown in Fig. 4. The primary cyclone fines passed down a vertical line to either the fines recycle injector or to a collecting drum. An incremental sampler was installed in the line immediately above the collection drum. The secondary cyclone fines were discharged directly into a sealed sample pot.

1.4 Coal and acceptor preparation

1.4.1 The Fluostatic drier/sample house crusher system

The coal for Task 1 was prepared using the Fluostatic/sample house system shown in schematic form in Fig. 5. The coal, as supplied, was fed through a roll crusher which produced a top size of 3/8 in. This was fed, by a screw feeder, into a Fluostatic fluidised bed drier operating at a fluidising velocity of 12 ft/s. The elutriated fines were collected in a cyclone and pneumatically conveyed together with bed overflow material, to an intermediate hopper. From there the coal was fed to a vibrating screen of the appropriate size, ¼ in or 10 B.S. mesh (1680 μm). The oversize was fed to a hammer mill and then recycled to the screen. Coal transport in this section of the plant was by screw feeders. The prepared coal from the screen was conveyed pneumatically either to the 36 in combustor coal hopper or to a storage hopper. The throughput of the plant was 2 tons per hour.

1.4.2 The Atritor plant

The limestones and dolomite for Task 1 were prepared using the Atritor plant, shown in schematic form in Fig. 6. The stone, as supplied, was loaded into the feed hopper by an elevator. It was then metered by a rotary table into a disperse phase drier and carried by the hot gas to the Atritor mill, which was a disk attrition mill. The gas also passed through the mill and transported the stone to a cyclone where it was separated. The stone passed to a vibrating screen of the appropriate size ¼ in or 10 B.S. mesh (1680 µm), and the oversize, about 10%, was recycled to the feed hopper. The prepared stone was collected in drums. The throughput of the plant was ½ ton per hour.

1.5 The coal and acceptor feeding systems

The arrangement of the coal and acceptor feeding systems is shown in Fig. 1. The basic design of the three systems was identical. The solids flowed by gravity into the rotary valve which metered the supply into an air stream. The feed rate was determined by the size and the number of pockets in the rotary valve and the speed of rotation. A pressure balancing line connected the coal transport line to the hopper top in order to prevent backflow of air through the rotary valve. Both the coal and acceptor feed lines incorporated a diverter valve and sample vessel. The sampling systems were designed to allow an uninterrupted flow of transport air. The capacities of the hoppers and the range of feed rates available were:-

	Capacity	Feed rates
Coal hopper	10 ton	40 - 400 lb/h
Large acceptor hopper	5000 lb	20 - 200 lb/h
Small acceptor hopper	1000 lb	10 - 70 lb/h

1.6 The cooling system

The cooling system is shown in Fig. 1. The steam leaving the tubes in the bed was desuperheated by a water spray, condensed, and recycled to the bed tubes and desuperheater spray. The water used in the cooling system was de-ionised and de-oxygenated.

1.7 Instrumentation

The plant was well automated and was operated by a pneumatic system from a central control room.

The air and gas flow rates were measured by orifice plate units. The solids feed rates were determined from the rotary valve speed of rotation, using the results of calibration tests. The output solids were collected and weighed. The fines recycle rate was calculated from the temperature drop in the fines due to a cooling coil on the recycle line. Pressures were measured by open-ended 3/16 in diameter probes maintained clear by a nitrogen bleed. Temperatures were measured by 'Pyrotenax' sheathed chromel/alumel thermocouples. The flow rates, pressures and temperatures were recorded on a punched tape data logger in addition to being recorded or indicated on the control panel.

The bed height was calculated from the ratio of the total bed pressure-drop to pressure-drop across 8 in of the bed. The height was normally controlled automatically by a pressure ratio controller operating the ash offtake rotary valve.

The water flow rate to the cooling tubes could be controlled either manually or by an automatic controller which adjusted the flow to maintain a set bed temperature.

A continuous gas sample was extracted 5 ft after the secondary cyclone for SO_2 determination by an infra-red analyser (IRA). The SO_2 concentration was indicated and recorded on the control panel. Gas samples were taken at a probe 4 ft after the cyclone for SO_2 determination by other methods, and for measurement of other constituents, as described in Section 2.4. The SO_2 concentrations indicated by the infra-red analyser were found to be consistently about 12% below the mean values obtained by the iodine method, Fig. 8.

2. GENERAL OPERATING PROCEDURES

2.1 Plant start-up

Before start-up, the plant services were checked and the solids rotary feed valves were calibrated for the particular coal and acceptor to be used. The combustor was heated by passing hot gas through the fluidising air system; the hot gas was produced by burning natural gas and then moderating the temperature to 1300°F by additional air. The starting bed material was fed to the combustor when the exit gas temperature was about 300°F and the coal was fed when the bed temperature had risen to 850°F. As the temperature increased, the fluidising air flow was reduced manually in order to prevent the fluidising velocity exceeding that for the first test condition. A low water flow was maintained through the cooling tubes once the coal feed was started, in order to purge nitrogen from the cooling system. As the bed temperature approached that required for the first test, the water flow was changed to automatic control to maintain the set temperature. The air and coal feed rates were then adjusted to the required values for the first test and acceptor feed was started, if required. This start-up procedure was normally completed in about 8 hours.

2.2 Establishment of equilibrium for a test

Once an operating condition was established, the plant was operated under automatic control until equilibrium was reached. For the purposes of the present work this was defined as being a condition at which three successive SO_2 determinations by the iodine method, taken at intervals of ½ h, were in agreement. If a mass balance was not to be carried out, for example when determining the datum SO_2 concentration at the start of each test series, the plant data sheets were then completed and temperatures, pressures and flow rates were recorded on the data logger.

For Test Series 2 to 6, the specified operating condition was that the concentration of oxygen in the off gas should be

2.5 to 3.5%. Because of this it was necessary to correct any variation in oxygen concentration during the stabilising period by adjusting the coal feed rate, which of course, also necessitated adjusting the additive feed rate. The time required to reach equilibrium conditions was about 6 hours.

2.3 Plant shut-down

The normal manual shut-down procedure was used throughout the A.P.C.O. programme; there were no emergency shut-downs due to power failures, etc. The coal feed rate was stopped and the bed temperatures reduced to 750°F over a period of 2 hours in order to avoid thermal shock to the bed tubes. The air flow rate was increased in order to maintain the fluidising velocity as the bed temperature fell. Coal and acceptor transport air were continued to prevent blockage of the lines. The bed material was then discharged into drums and the fines collection pots were emptied. When the cooling system temperature fell below 212°F the circulating pump was stopped and nitrogen was admitted to relieve the vacuum. The fluidising air was stopped and the services were shut off. Finally all the collecting pots and rodding-points were emptied to avoid contamination of the next run.

2.4 Mass balance procedure

The equilibrium conditions were maintained for a minimum of 4 hours and during this time sufficient samples were taken to carry out a balance. The only exception was during the latter tests of Series 3 when shortage of time necessitated a reduction to 3 hour periods.

At the start of each balance a sample of bed ash of approx. 1 lb was taken to determine the chemical and size analysis of the initial bed. The apparatus used is shown in Fig. 7. A second bed ash sample was taken upon completion of each balance to give the final bed conditions. When possible an offtake ash sample was also taken to give supporting information regarding the bed, but this sample was only a spot sample of about 10 lb and was obviously only possible when there was an overflow of ash.

The primary fines were sampled throughout the balance using an incremental sampler designed to take a full cross-sectional sample of the entire fines flow. Twenty increments were taken each hour of the balance and the hourly samples bulked to give one sample of about 40 lb. This quantity was then reduced by rotary divider to give a representative sample of about 1 lb. The entire output of secondary fines was collected during each balance and was likewise reduced by rotary dividing to give a 1 lb sample. Samples of exhaust dust were obtained from a probe 4 ft after the secondary cyclone by extracting isokinetically a known volume of exhaust gas and passing it through a weighed filter. Four such dust samples were taken over the balance period and these were combined to give one sample for analysis. Coal and additive were sampled directly from the input lines immediately before each balance. In Test Series 1 the samples were bulked to give an incremental sample for the week, but in all other series samples were retained for each test.

Gas samples were taken at two probes in the vertical line from the secondary cyclone, 4 and 5 ft above the cyclone respectively. The upper probe was used only for the infra-red SO_2 analyser, and a continuous record was obtained. The lower probe was used for all other gas analyses, as follows:

(a) Samples were taken in evacuated vessels for analysis of O_2, CO_2, CO and CH_4 by chromatograph. A minimum of two such samples were taken during the mass balance. The minimum level of detection of CO and CH_4 was 0.02%, (200 p.p.m.)

(b) By means of a vacuum pump, gas was bubbled through a solution of iodine for SO_2 determination. The volume of gas required to decolourise a solution of known concentration was recorded. A determination of SO_2 by this method was carried out every half hour.

(c) Samples were taken for determination of NO_x by Saltzman's method by bubbling gas through distilled water, to remove SO_2, and then passing through a sample bottle. The sample was taken after allowing sufficient gas to purge air from the system. Two samples were taken for NO_x during tests in Test Series 4, 5 and 6.

(d) By means of a vacuum pump, gas was bubbled through a solution of hydrogen peroxide except when carrying out (a), (b) and (c) above. The solution was analysed for SO_2, Cl and NH_3.

Throughout the balance, at hourly intervals, all solid products were weighed and plant data sheets completed. In addition the feed rates of coal, acceptor and air, the plant temperatures and pressures were recorded hourly on the data logger.

2.5 Data processing

The data logger tape from each test was processed by computer to calculate the mean feed rates, plant temperatures and pressures for the mass balance period. The feed rates, measured solids output rates and chemical analyses of the input and output streams were then used to calculate by computer the mass balances.

The major factor in the mass balance which was not measured was the flow-rate of flue gas, which it was necessary to estimate. Since the gas analysis was carried out on a dry volume basis, the dry volume was estimated rather than mass flow-rate of flue gas. The estimate was obtained by correcting the feed air flow-rate for the volume changes which occurred due to the following reactions:-

(i) $4H \text{ (coal)} + O_2 \longrightarrow 2H_2O \text{ (liquid)}$

(ii) $2O \text{ (coal)} \longrightarrow O_2$

(iii) $2C + O_2 \longrightarrow 2\,CO$

(iv) $MgCO_3 \longrightarrow MgO + CO_2$

(v) $CaCO_3 \longrightarrow CaO + CO_2$

(vi) $CaO + \frac{1}{2}O_2 + SO_2 \longrightarrow CaSO_4$

The volume changes due to (i) and (ii) were calculated assuming that all the hydrogen and oxygen in the coal were released. The increase due to (iii) was calculated from the measured concentration of CO in the flue gas. With limestone the net effect of (v) and (vi) was small and this was usually neglected. Thus for tests without acceptor and most tests with limestone the flue gas flow-rate was calculated as:

$$\text{Flue gas flow-rate} = \frac{\text{Air} + 379 \times \text{Coal Feed Rate} \times (\text{O Content}/32 - \text{H Content}/4)}{(1 - 0.5 \times \text{CO in Flue Gas})} \text{ SCFH}$$

For tests with dolomite, and also for Test 5.4 with limestone, the volume changes due to (iv), (v) and (vi) were also taken into account.

The following mass balances were carried out:-

(i) Total — In this, mass flow-rate of dry flue gas was calculated from its composition and a hydrogen balance was assumed. For Test Series 4 and 6 with dolomite and Test 5.4 at a Ca/S ratio of 6, the CO_2 from calcination was added to the flue gas rate as calculated above.

(ii) 'Ash' — This is a balance for the inorganic solids, i.e. ash and acceptor. No allowance was made for the weight changes due to calcination of $CaCO_3$ (except in Test 5.4) and formation of sulphate. Where dolomite was used, Test Series 4 and 6, it was assumed that the $MgCO_3$ was completely calcined and the equivalent calcined product rate was used in the balance.

(iii)	'Carbon'	This is a balance for the organic carbon in the coal and is directly relevant to the combustion process. Allowance was made for the CO_2 in the flue gas arising from calcination only in the tests with dolomite and in Test 5.4.
(iv)	Nitrogen	This balance serves as a check on the accuracy of the flue gas analysis.
(v)	'Oxygen'	This is a balance for the oxygen in the air and the organic oxygen in the coal. It is directly relevant to the combustion process. Allowance was made for the oxygen as CO_2 from calcination only in tests with dolomite and Test 5.4.
(vi)	Sulphur	This is a balance for the total sulphur content of the coal, using the mean SO_2 concentration measured by the iodine method.
(vii)	Calcium	This is a balance for the total calcium in the coal and acceptor.
(viii)	Magnesium	This is a balance for the magnesium in the acceptor and was carried out only for tests with dolomite.

The following parameters were calculated from the flow rates in the mass balance:-

(i) Excess air level, defined as:

$$\text{Excess air} = \frac{\text{Feed air - Stoichiometric air for coal feed rate}}{\text{Stoichiometric air for coal feed rate}} \times 100\%$$

(ii) Carbon loss, defined as:

$$\text{Carbon loss} = \frac{\text{Unburnt carbon output rate}}{\text{Total carbon output rate}} \times 100\%$$

The carbon loss is based on the total measured carbon output rate since this is considered to be a more accurate estimate of the carbon input rate than that based on the coal feed rate and chemical composition.

(iii) Sulphur retention, defined as:

$$\text{Sulphur retention} = \left\{1 - \frac{\text{Sulphur in flue gas}}{\text{Total sulphur input}}\right\} \times 100\%$$

(iv) Ca/S mol ratio, defined as:

$$\text{Ca/S mol ratio} = \frac{\text{Mols of Ca in additive feed}}{\text{Mols of S in coal feed}}$$

3. RESULTS

3.1 Test Series 1

The objective of the test series was to obtain data on the effects of bed temperature and Ca/S mol ratio on sulphur dioxide emission with Pittsburgh coal and American limestone. The intended nominal operating conditions were:

Coal	Pittsburgh, prepared to - 10 BS mesh
Acceptor	Limestone 18, prepared to - 10 BS mesh
Ca/S mol ratio	0,1,2 and 3
Fluidising velocity	3 and 4 ft/s
Bed temperature	1380, 1470 and 1560°F
Bed depth	2ft
Excess air	10 to 20%
Fines recycle	System not in operation

3.1.1 Description of Test Series 1

The tests series was sub-divided into three sections, each comprising one week of plant operation, as follows:

3.1.1.1 Test Series 1.1

The objective for Test Series 1.1 was to carry out an extended test, without limestone addition, at a fluidising velocity of 4ft/s and a bed temperature of 1470°F.

The test series was carried out from 19 to 21 November, 1970. The plant was started up using an initial bed of Newdigate shale prepared to have a top size of 1/16 in. The required operating conditions were maintained for 26 hrs and a four hour mass balance designated Test 1.1 was carried out towards the end of this period.

The water cooled coal feed inlet for the coking coal, which was in use for the first time, functioned satisfactorily.

During the test series gas samples were withdrawn for SO_2 analysis by the iodine method both after the cyclones and at three positions in the freeboard cross-section at 22 in above the bed surface (shown in Fig. 3). Some difficulty was experienced with air leaks into the sampling system and following this test series, the sampling probes were modified and the air leaks eliminated in subsequent test series.

3.1.1.2 Test Series 1.2

The objective for Test Series 1.2 was to determine the optimum bed temperature for subsequent experimental work.

The test series was carried out from 17 to 19 December, 1970. The plant was started up using ash from Test Series 1.1 together with about 10% of fresh Newdigate shale. A test was carried out without limestone addition at 4 ft/s and 1470°F, Test 1.2, which was followed by three tests, Tests 1.3, 1.4 and 1.5 with limestone addition at a Ca/S mol ratio of 2 and bed temperatures of 1470, 1380 and 1560°F respectively. In the period between Tests 1.2 and 1.3, there was a coal feed blockage and it was necessary to slump the bed for a period of two hours in order to clear the line. On re-starting it was necessary to add 70 lb of shale to re-establish a 2 ft bed.

The limestone feeding system was used for the first time in this test series and no difficulties were encountered apart from a blockage of short duration prior to Test 1.5. The continuous infra-red SO_2 analyser was also commissioned during the test series. The initial results from this did not agree with those obtained by titration with iodine solution and were obviously low. Between Tests 1.3 and 1.4 a heater was fitted between the sample point and the instrument. This modification immediately gave rise to higher SO_2 reading, but even so in this, and all subsequent tests, the infra-red analyser gave values about 12% below the mean result obtained by the iodine method. Fig. 8 compares the SO_2 concentrations using the two methods from this test and all subsequent test series.

3.1.1.3 Test Series 1.3

The objectives for Test Series 1.3 were to obtain data on the effect of the Ca/S mol ratio on sulphur dioxide emission at a fluidising velocity of 4 ft/s with a bed temperature of 1560°F and to operate at 3 ft/s with a bed at 1470°F in order to allow direct comparison with data from the 6 in combustor, Task V.

The test series was carried out from 11 to 15 January, 1971. The plant was started up without limestone addition using an initial bed of Newdigate shale prepared to have a top size of 1/16 in. When steady operating conditions were achieved at 4 ft/s, 1560°F, the datum SO_2 concentration without additive was recorded. Limestone addition was then started and Tests 1.6, 1.7 and 1.8 were carried out at stoichiometric ratios of 1, 2 and 3, respectively. The limestone feed rate was reduced back to a ratio of 1 and a further test, Test 1.9, was carried out.

The bed was removed and a new bed of shale was established. The plant was re-started at 3 ft/s, 1470°F without limestone addition and the SO_2 concentration was recorded. Tests 1.10 and 1.11 were then carried out with limestone addition to give stoichiometric ratios of 1 and 2, respectively.

Inspection of the combustor interior after the test series revealed a split, about 1 in long, in one of the bed temperature control tubes. There was no means of determining when this damage had occurred.

3.1.2 Results of Test Series 1:

The experimental operating conditions through Test Series 1 are summarised in Table 1.1. The input and output size distributions and chemical analyses are detailed in Tables 1.2 to 1.8. The flue gas analyses are given in Table 1.9, with the variation in the SO_2 concentration with time plotted in Figures 1.1 to 1.14. Mass balances and calculated operating parameters are given in Tables 1.10 to 1.20. The pressure drops and temperature distributions through the plant are in Tables 1.21 and 1.22 respectively. The positions of the thermocouples in the combustor during the test series are given in Fig. 1.15.

The carbon loss data, Tables 1.10 to 1.20, indicate that without fines recycle the combustion efficiency at 4 ft/s was about 92%, independent of bed temperature in the range 1380 to 1560°F. Because of this, the oxygen concentration in the off-gas at 10% excess air was about 3.5%. The off-gas temperature, shown in Table 1.22, was unaffected by bed temperature, indicating that more combustion was occurring in the freeboard at the lower temperatures. Between 5 and 10% of the total heat release occurred in the freeboard. (The lower off-gas temperature in Test 1.2 is probably due to the refractory of the freeboard not being at an equilibrium temperature). The combustion efficiency at 3 ft/s was not significantly different from that at 4 ft/s, but the off-gas temperature was lower, indicating that a higher proportion of the combustion was occurring within the bed.

The bed temperature was uniform to within about ± 10°F, but there was a tendency for the maximum temperature to be recorded at the thermocouple 8 in above the coal feed point, Table 1.22.

The results from datum tests 1.2, and those prior to tests 1.6 and 1.10 (Tables 1.9a to 1.9d) show that over the range 3-4 ft/s fluidising velocity did not affect sulphur release. The low value for Test 1.1 was due to the feed coal having a lower sulphur content than in subsequent tests.

The reductions in SO_2 emission with addition of limestone 18 are given in Table 1.23 and the results are plotted against the added Ca/S mol ratio in Fig. 1.16. The curves show that increasing the Ca/S ratio reduces the emission of SO_2. The additive is somewhat more effective at 3 ft/s than at 4 ft/s but considerably less effective at 1380°F than at 1470 and 1560°F

The gas samples taken 2 ft above the bed surface showed a marked radial SO_2 concentration gradient, Fig. 1.1.

Centre	2800 p.p.m.
6 in radius	1750 p.p.m.
12 in radius	14000 p.p.m.

In comparison, the concentration at the stack was 1750 p.p.m.

3.2 Test Series 2

The objective of the test series was to obtain data on sulphur dioxide emission with Pittsburgh coal at a fluidising velocity of 8 ft/s, using coarser coal and limestone size distributions and at 4 ft/s, using fine limestone with recycle of the elutriated fines. The intended nominal operating conditions were:-

Coal	Pittsburgh, prepared to - ⅛ in.
Acceptor	Limestone 18 prepared to - ⅛ in and - 120 B.S. mesh.
Ca/S mol ratio	0, 1, 2 and 3.
Fluidising velocity	4 and 8 ft/s.
Bed temperature	1560°F.
Bed depth	2 ft.
Flue gas oxygen	2.5 to 3.5%.
Fines recycle	System in operation for a single test with - 120 mesh limestone.

3.2.1 Description of Test Series 2

The test series was carried out from 26th to 29th January, 1971. The plant was started up without limestone addition using an initial bed of Newdigate shale prepared to have a top size of ⅛ in. When the operating conditions were steady at a fluidising velocity of 8 ft/s, the datum SO_2 concentration without additive was recorded. Tests 2.1, 2.2 and 2.3 were then carried out with addition of the - ⅛ in limestone to give stoichiometric ratios of 1, 2 and 3 respectively. The bed was replaced by fresh - ⅛ in shale and the plant restarted at a fluidising velocity of 4 ft/s. After 12 hours operation the SO_2 concentration was constant and was recorded as the datum. The -120 B.S. mesh limestone was then fed to give a stoichiometric ratio of unity for Test 2.4. During the following 15 hours it was necessary to adjust the coal feed rate occasionally in order to maintain the required oxygen concentration of 2.5% to 3.5% above the bed. These adjustments delayed the start of the mass balance which was eventually carried out 27 to 31 hours after the restart.

The limestone feed rate was then increased to give a stoichiometric ratio of 2, but continuous difficulty was experienced in feeding the limestone and despite changes in operating procedure, the feed rate was variable to the point of complete stoppage. After 14 hours it was decided to discontinue the programme and to attempt a short test at a fluidising velocity of 3 ft/s and a stoichiometric ratio of 1, in order to allow direct comparison with Task V. This condition was successfully maintained for about 2 hours and is designated Test 2.5, although no mass balance was carried out.

On removal of the fine limestone rotary valve after shut-down, it was found that there was a partial blockage caused by damp limestone. This accounted for the erratic feed rate obtained. The source of the water was thought to be the nitrogen bleeds around the hopper outlet.

NO_X determinations were carried out during the datum test and Tests 2.1 and 2.2 by staff from BCURA using Saltzman's method.

3.2.2 Results of Test Series 2

The experimental operating conditions through Test Series 2 are detailed in Table 2.1. The input and output size distributions and chemical analyses are detailed in Tables 2.2 to 2.8 and the flue gas analyses in Table 2.9, with the variation in the SO_2 concentration with time plotted in Figures 2.1 to 2.5. Mass balances and calculated operating parameters are given in Tables 2.10 to 2.13. The pressure drops and temperature distributions through the plant are shown in Tables 2.14 and 2.15 respectively. The positions of the thermocouples in the combustor during the test series are given in Fig. 2.6.

The combustion efficiency without fines recycle in the tests at 1560°F, at a fluidising velocity of 8 ft/s was about 87% for the mean excess air level of 3% which is lower than the efficiency of 92% obtained at 4 ft/s with 10% excess air in Test 2.4 and in Test Series 1. The lower excess air level at 8 ft/s was necessary in order to achieve the specified oxygen concentrations. The steam injection rate to the freeboard necessary to limit the off-gas temperature indicates that a higher proportion of the combustion was occurring in the freeboard during tests at 8 ft/s, Table 2.15.

At 8 ft/s there was a hot spot in the bed above the coal feed point, $60^{o}F$ above the mean bed temperature at a point 8 in above the feed, thermocouple N4, Table 2.15. The maximum temperature difference between this point and the coolest point in the bed was $100^{o}F$.

The reductions in SO_2 emission achieved with the limestone 18 are given in Table 2.16 and plotted against the Ca/S mol ratio in Fig. 2.7. Comparison with Fig. 1.16 shows that there is about 20% less reduction in emission at 8 ft/s than at 4 ft/s. The reduction with 120 B.S. mesh (-125 μm) stone at 3 and 4 ft/s is close to that obtained with 10 B.S. mesh (-1680 μm) stone in Test Series 1, i.e. grinding the limestone more finely had no significant effect.

The mean NO_X emission without limestone was 424 p.p.m., Table 2.9. The NO_X emission increased to 470 p.p.m. with limestone addition at a Ca/S of 1.1, and increased further to 515 p.p.m. at a Ca/S of 2.3.

3.3 Test Series 3

The objective of the test series was to obtain data on sulphur dioxide emission with U.K. Welbeck coal and U.K. limestone. The intended nominal operating conditions were:

Coal	U.K. Welbeck prepared to -⅛ in.
Acceptor	U.K. limestone prepared to -⅛ in.
Ca/S mol ratio	0, 2 and 3.
Fluidising velocity	4 and 8 ft/s.
Bed Temperature	1560°F
Bed Depth	2 and 4 ft.
Flue-gas oxygen	2.5 to 3.5%
Fines recycle	System in operation for a single test at 4 ft/s.

3.3.1 Description of Test Series 3

The test series was carried out from 15 to 19th February, 1971. The plant was started up without limestone addition using an initial bed of Newdigate shale prepared to have a top size of ⅛ in. Since a new coal was being used a complete mass balance was carried out without limestone addition, Test 3.1. This was carried out at 8 ft/s with a 2 ft deep bed. The bed temperature control during the test was poor, varying within ±25° of the set value, and this was thought to be due to an erratic coal feed rate. Consequently, before continuing with the program the plant was shut down to allow the coal feed system to be dismantled and checked. The plant was restarted after a delay of 12 hours and subsequently the temperature control was better. Test 3.2 was carried out with limestone addition at a stoichiometric ratio of two, but the limestone feed rate in this test was erratic. Subsequently, the limestone feed valve rotor was replaced and a further test was carried out at the same nominal operating conditions, Test 3.3. The limestone addition rate was then increased to a stoichiometric ratio of three for Test 3.4.

After this test was completed an additional experiment, not in the original programme was carried out. It had been noticed, during the period when the bed temperature was varying, that the SO_2 concentration indicated by the infra-red analyser was also varying in phase. The apparent rapid response to temperature was investigated by increasing the bed temperature to 1630°F decreasing to 1470° and increasing back to 1560° during a period of 1 hour.

Fresh shale was added to the bed to give a bed height of 4 ft for Test 3.5. In this and the subsequent test, the mass balance period was reduced to 3 hours because of the low stock of prepared coal remaining. For the final test, Test 3.6, the bed height was reduced to 2 ft and the fluidising velocity was 4 ft/s. There was insufficient of the prepared coal available to carry out the scheduled test with fines recycle.

3.3.2 Results of Test Series 3

The experimental operating conditions through Test Series 3 are summarised in Table 3.1. The input and output size distribution and chemical analyses are detailed in Tables 3.2 to 3.8 and the flue gas analyses in Tables 3.9, with the variation in the SO_2 concentration with time plotted in Figures 3.1 to 3.7. Mass balances and calculated operating parameters are given in Tables 3.10 to 3.15. The pressure drops and temperature distributions through the plant are in Tables 3.16 and 3.17 respectively. The positions of the thermocouples in the combustor during the test series are given in Fig. 3.8.

The mean combustion efficiency in these tests with Welbeck coal at 8 ft/s was 89%, a slight improvement over the 87% obtained in Series 2 for Pittsburgh coal. Thus a lower coal feed rate could be used to attain the specified oxygen concentrations, giving a mean excess air level of 7% in comparison with 3% in Series 2.

The bed temperatures were more uniform than with Pittsburgh coal and there was no 'hot spot' above the coal feed. Even so there were differences of about 40°F between maximum and minimum temperatures within the bed.

The reductions in SO_2 emission are given in Table 3.18 and are plotted against the Ca/S mol ratio in Fig. 3.9. The result of Test 3.2 has been neglected in drawing the curve in Fig. 3.9 because it appears to be in error. The reduction at 8 ft/s is about 5% less than that obtained with Pittsburgh coal and U.S. limestone in

Test Series 2. The single result at 4 ft/s is low in comparison with those in Series 1. The SO_2 emission was not affected when the bed height was increased from 2 ft to 3.8 ft.

The variation of SO_2 concentration during the bed temperature survey is shown in Fig. 3.5. The SO_2 concentration responded almost immediately to a change in bed temperature. The SO_2 reductions during the survey are given in Table 3.19 and plotted in Fig. 3.10. The datum SO_2 concentration measured by the IRA was surprisingly high, and was not used. Instead, a datum value was calculated as 12% below the concentration obtained by the iodine and H_2O_2 methods, i.e. allowing for the usual instrument off-set. There appears to be an optimum temperature for SO_2 reduction of about 1450°F and the reduction falls rapidly as the temperature is increased.

3.4 Test Series 4

The objective of the test series was to determine the effects of bed temperature, Ca/S mol ratio and fluidising velocity on sulphur dioxide emission when using dolomite as additive. Also, tests were to be carried out under conditions closely resembling those used in Task II, in order to make a direct comparison between pressurised and unpressurised operation. The intended nominal operating conditions were:

Coal	Pittsburgh prepared to - 10 B.S. mesh.
Acceptor	Dolomite 1337 prepared to - 10 B.S. mesh.
Ca/S mol ratio	0, 1 and 2.
Fluidising velocity	2 and 4 ft/s.
Bed Temperature	1380, 1470 and 1560°F.
Bed depth	2 and 4 ft.
Flue-gas oxygen	2.5 to 3.5%.
Fines recycle	System in operation for a single test at 2 ft/s.

3.4.1 Description of Test Series 4

The test series was carried out from 2 to 5 March, 1971. The plant was started up without limestone addition using an initial bed of Newdigate shale prepared to have a top size of 1/16 in. When the operating conditions were steady at a fluidising velocity of 4 ft/s and a temperature of 1470°F, the datum SO_2 concentration without additive was recorded. Tests 4.1, 4.2 and 4.3 were then carried out with dolomite addition at a stoichiometric ratio of 2 and temperatures of 1470, 1380 and 1560°F respectively.

The bed temperature was then changed to 1470°F and the alternative dolomite feed system was brought into operation for tests at a nominal stoichiometric ratio of 1. Test 4.4 was carried out at a fluidising velocity of 4 ft/s. Shale was then added to increase the bed height to 4 ft and the fluidising velocity was decreased to 2 ft/s for the first of the tests at the pressurized combustor operating conditions, Test 4.5. The SO_2 levels in Tests 4.4 and 4.5 were considerably lower than had been expected and it was suspected that the dolomite feed rate was in error. Consequently, the dolomite feed was diverted from the bed, in order to measure its rate and it was found to be almost double that intended.

The reason for this higher rate through the rotary valve than in the pre-test calibration is not known. After several re-calibration checks over a range of rotary valve rotation rates it was confirmed that the feed rates were consistently higher than before.

The limestone feed line was re-connected to the bed and a final Test 4.6, was carried out at 2 ft/s with the fines recycle system in operation. About 400 lb of fines had to be added to the bed in order to establish the recycle flow.

Test Series 4 was the first in which NO_X determinations were made by CRE staff. Samples were taken after the cyclones and Saltzman's method was used.

3.4.2 Results of Test Series 4

The experimental operating conditions throughout the series are detailed in Table 4.1. The input and output size distributions and chemical analyses are given in Tables 4.2 to 4.8 and the flue gas analyses in Table 4.9, with the variation in the SO_2 concentration with time plotted in Figures 4.1 to 4.7. Mass balances and calculated operating parameters are given in Tables 4.10 to 4.15. The pressure drops and temperature distributions through the plant are given in Tables 4.16 and 4.17 respectively. The positions of the thermocouples in the combustor during the test series are given in Fig. 4.8.

The combustion efficiency without fines recycle at 4 ft/s was about 91% and was independent of bed temperature; this is in good agreement with the result in Test Series 1. There was no significant improvement on decreasing the velocity to 2 ft/s and increasing the bed height to 4 ft. However total primary fines recycle, at a rate of about five times the coal feed rate, increased the combustion efficiency to 99.3%. The temperature distributions through the combustor confirmed the findings of Series 1.

The reductions in SO_2 emission with dolomite 1337 are given in Table 4.18 and plotted against the Ca/S mol ratio in Fig. 4.9. At 4 ft/s there was about 10% less reduction with dolomite than with limestone 18, (Test Series 1, Fig. 1.16). Unlike limestone, the reduction in emission did not become less when the bed temperature was reduced to 1380°F. The SO_2 reduction at 2 ft/s with dolomite was close to that with limestone at 3 ft/s, again indicating a lower effectiveness. With fines recycle at 2 ft/s, the SO_2 concentration was reduced to 20 p.p.m., a reduction of 99%.

The NO_X emission at 4 ft/s with a 2 ft bed was about 240 p.p.m. for both 1470 and 1560°F. The NO_X emission increased to about 390 p.p.m. at 2 ft/s with a 4 ft bed. The single result with fines recycle indicates that recycle, with tne associated low SO_2 concentration, did not effect the NO_X emission;this is in contrast to Test Series 2 without fines recycle, where reduction of SO_2 emission did increase NO_X emission.

3.5 Test Series 5

The objectives of the test series were to determine the effects of bed height and fluidising velocity on sulphur dioxide emission with limestone addition, and also to test the effectiveness of a very high Ca/S mol ratio. The intended nominal operating conditions were:

Coal	Pittsburgh, prepared to -⅛ in.
Acceptor	Limestone 18, prepared to -⅛ in.
Ca/S mol ratio	0, 2 and 6.
Fluidising velocity	4 and 8 ft/s.
Bed temperature	1560°F.
Bed depth	2 and 4 ft.
Flue-gas oxygen	2.5 to 3.5%.
Fines recycle	System not in operation.

3.5.1 Description of Test Series 5

The test series was carried out from 17 to 22 March 1971. The plant was started up without limestone addition using an initial bed of Newdigate shale prepared to have a top size of ⅛ in. When operating conditions were steady at a fluidising velocity of 4 ft/s and bed depth of 2 ft the datum SO_2 concentration without additive was recorded. Tests 5.1 and 5.2 were then carried out with limestone addition to give a stoichiometric ratio of 2 at fluidising velocities of 4 and 8 ft/s respectively. During these tests the SO_2 concentration was determined in the freeboard using a movable probe 24 in. above the bed Fresh shale was added to increase the bed height to 4 ft for Test 5.3 at 8 ft/s with stoichiometric ratio of 2. The limestone feed rate was increased to give a stoichiometric ratio of 6 for Test 5.4. On completion of the mass balance of this test it had been intended to continue operating the plant for a further 24 hours at the same operating conditions. However immediately after the mass balance there was a coal feed failure and it was necessary to shut down the plant to allow the coal feed system to be examined. The plant was re-started after a period of 12 hours and operated under steady conditions for a period of 20 hours, designated Test 5.5, but no mass balance was carried out.

3.5.2 Results of Test Series 5

The experimental operating conditions through Test Series 5 are detailed in Table 5.1. The input and output size distributions and chemical analyses are detailed in Tables 5.2 to 5.8 and the flue gas analyses in Table 5.9, with the variation in the SO_2 concentration with time plotted in Figures 5.1 to 5.6. Mass balances and calculated operating parameters are given in Tables 5.10 to 5.13. The pressure drops and temperature distributions through the plant are in Tables 5.14 and 5.15 respectively. The positions of the thermocouples in the combustor during the test series are given in Fig. 5.7.

The combustion efficiencies of 85 and 81% in Tests 5.3 and 5.4 at 8 ft/s without fines recycle are lower than in Test 5.2 and in Test Series 2 (87%) because of the lower excess air level in Tests 5.3 and 5.4. The hot spot above the coal feed was considerably less marked than in Series 2, being only about 30°F above the mean bed temperature in Test 5.2, and almost non-existent in the deeper beds of Tests 5.3 and 5.4. It should be noted that there were tubes in only the bottom 2 ft of the bed.

The reductions in SO_2 emission are given in Table 5.16 and plotted against the Ca/S mol ratio in Fig. 5.8. The single datum SO_2 concentration value taken at the stack is surprisingly low, and has not been used. The value used, 2400 p.p.m., was calculated by correcting the value during Test Series 2 for the higher sulphur content of the coal in this series. The value is also justified by the IRA datum of 2060 p.p.m., which value is usually about 12% below that of the iodine method, Fig. 1.8, indicating an iodine value of about 2320 p.p.m. The SO_2 reductions in Tests 5.1, 5.2 and 5.3 are in reasonable agreement with Test Series 1 and 2, Figs. 1.16 and 2.7. Tests 5.4 and 5.5 demonstrate that almost complete reduction of SO_2 can be achieved by using a high Ca/S mol ratio.

The gas samples taken 2 ft above the bed surface show a marked radial SO_2 concentration gradient, Fig. 5.1 and Table 5.17 as in Test Series 1. It is not possible to determine whether or not reaction of SO_2 is occurring in the freeboard, from these results.

The NO_X concentration in the datum test at 4 ft/s was about 300 p.p.m., in reasonable agreement with Test Series 4. At 8 ft/s with limestone addition at a Ca/S mol ratio of 1.6 the NO_X increased to 450 p.p.m. and there was a further increase to 550 p.p.m. on raising the limestone feed rate to give Ca/S of 6. However in the later stages of Test 5.5, NO_X concentrations of 320 p.p.m. were measured. If these final values were neglected, it could be concluded that the NO_X concentration increases as SO_2 is reduced by limestone addition, in agreement with Test Series 2; (except in the case of fines recycle) but this would be difficult to justify.

3.6 Test Series 6

The objective of the test series was to obtain data on sulphur dioxide emission when using coarse dolomite additive at a fluidising velocity of 8 ft/s with deep beds. The intended nominal operating conditions were:

Coal	Pittsburgh, prepared to -¼ in.
Acceptor	Dolomite 1337, as received (-¼ in. + 30 B.S.S.)
Ca/S mol ratio	0, 2 and 4.
Fluidising velocity	8 ft/s.
Bed temperature	1560°F and a survey over the range 1420 to 1620°F.
Bed depth	2, 4 and 9.5 ft.
Flue-gas oxygen	2.5 to 3.5%.
Fines recycle	System not in operation.

3.6.1 Description of Test Series 6

The test series was carried out from 29th March to 2 April, 1971. Prior to the test series the bed pressure drop probes were modified and the steam inlet line was raised to allow operation with the deep bed envisaged. The plant was started up without dolomite addition using a 2 ft deep bed of Newdigate shale prepared to have a top size of ¼ in. When the operating conditions were steady, the datum SO_2 concentration without additive was recorded. Additive feeding was commenced at a stoichiometric ratio of 2 for Test 6.1. On completing this test the dolomite feed was increased to a ratio of 4 for Test 6.2. However there was a dolomite feed failure part way through the mass balance and it was necessary to slump the bed for a period of 1 hour while repairs were made. On re-starting the conditions were again stabilised and a complete mass balance for Test 6.2 was carried out. The bed depth was then increased to 4 ft by adding ash from previous tests. Test 6.3 was carried out, maintaining the stoichiometric ratio at 4. After this test, the bed temperature was increased to 1620°, decreased to 1420° and returned to 1560°F over a period of one hour. During this period the air, coal and dolomite feed rates were maintained constant.

The bed was then slumped in order to allow the coal and dolomite hoppers to be re-filled. On re-start the fluidising velocity was maintained at 4 ft/s while shale and ash were added to give a bed depth of about 7 ft. The fluidising velocity was then increased to 8 ft/s to give an expanded bed depth of 9 ft. However this bed depth could not be maintained because of excessive elutriation, despite feeding the coarse dolomite at a stoichiometric ratio of 4, and the depth decreased to 6 ft over a period of about 12 hours. During this period the operating conditions were otherwise steady, and a four hour mass balance was carried out with a bed depth of about 7 ft, Test 6.4. A further mass balance was carried out at a steady bed depth of 6 ft, Test 6.5.

3.6.2 Results of Test Series 6

The experimental operating conditions through Test Series 6 are detailed in Table 6.1. The input and output size distributions and chemical analyses are detailed in Tables 6.2 to 6.8 and the flue gas analyses in Table 6.9, with the variation in the SO_2 concentration with time plotted in Figures 6.1 to 6.6. Mass balances and calculated operating parameters are given in Tables 6.10 to 6.14. The pressure drops and temperature distributions through the plant are in Tables 6.15 and 6.16 respectively. The positions of the thermocouples in the combustor during the test series are given in Fig. 6.7.

The combustion efficiency without fines recycle at 8 ft/s was in the range of 84 to 87%, in good agreement with Test Series 2 and 5. In Tests 6.3, 6.4 and 6.5, with deep beds, only a small quantity of steam was required to limit the off-gas temperature, indicating that a higher proportion of the combustion was occurring within the bed. As in Test Series 5, there was no hot spot above the coal feed point, Table 6.16.

The reductions in SO_2 emission are given in Table 6.17 and are plotted against the Ca/S mol ratio in Fig. 6.8. Comparison with Test Series 4, Fig. 4.9, indicate that there is about 15% less reduction at 8 ft/s than at 4 ft/s. The evidence on the effect of bed height at 8 ft/s is conflicting. Tests 6.2, 6.3 and 6.5 suggest that there is no effect, whereas Test 6.4 indicates an increase in efficiency of reduction with increasing height.

The variation of SO_2 concentration during the bed temperature survey is shown in Fig. 6.4. As in Test Series 3, the SO_2 concentration responded almost immediately to a change in bed temperature. The SO_2 reductions during the survey, based on an estimated IRA datum, are given in Table 6.18 and plotted in Fig. 6.9. There appears to be an optimum temperature for SO_2 reduction of about 1400°F and the reduction falls by 20% when the temperature is increased to 1650°F. The magnitude of this effect is perhaps surprising in view of the high Ca/S mol ratio of 5.3.

The NO_X concentration averaged 400 p.p.m. during the Test Series and there was no significant variation between the individual Tests.

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Table A.1.1.1. Operating conditions during Test Series 1

Coal	Pittsburg coal
Coal size (upper limit)	1680 µm
Acceptor	Limestone 18
Acceptor size (upper limit)	1680 µm
Fines Recycle	System not in operation

Test Series		1.1	1.2			
Test No.		1.1	1.2	1.3	1.4	1.5
Time from start of Test Series (hrs)	Start	18	8	33	46	56
	End	22	12	37	50	60
Ca/S mol ratio		0	0	2.2	2.2	2.2
Coal Rate lb/h dry		123	124	116	124	112
Fluidising Velocity ft/s		4.0	4.0	4.0	4.0	4.0
Bed Temperature ^{o}F		1470	1470	1470	1380	1560
Bed Height		2.3	2.2	2.2	2.2	2.2

Test Series		1.3							
Test No.		Datum	1.6	1.7	1.8	1.9	Datum	1.10	1.11
Time from start of Test Series (hrs)	Start	0	15	27	38	51	62	70	84
	End	1	19	31	42	55	64	74	88
Ca/s mol ratio		0	1.3	2.2	3.3	1.2	0	2.2	3.3
Coal Rate lb/h dry		116	116	121	124	124	97	97	94
Fluidising Velocity ft/s		4.0	4.0	4.0	4.0	4.0	3.0	3.0	3.1
Bed Temperature ^{o}F		1560	1560	1560	1560	1560	1470	1470	1470
Bed Height		2.2	2.2	2.1	2.2	2.1	2.3	2.3	2.1

Table A.1.1.2 - Chemical Analyses of coal

Test Series		1.1	1.2	1.3
Test Number		1.1	1.2-1.5	1.6-1.11
Proximate Analysis				
Total moisture	% a.r.	2.8	1.3	1.6
Ash	% a.r.	16.8	14.4	13.5
Volatile matter	% d.a.f.	39.7	41.2	41.1
Ultimate analyses				
Carbon	% d.b.	67.5	71.5	71.7
Hydrogen	% d.b.	4.2	4.5	4.5
Nitrogen	% d.b.	1.45	1.4	1.4
Sulphur	% d.b.	2.15	2.7	2.5
Oxygen + errors	% d.b.	5.2	4.3	4.4
Chlorine	% d.b.	0.14	0.09	0.1
Carbon dioxide	% d.b.	0.95	0.52	0.61
Ash analysis				
CaO	% d.b.	7.3	8.0	-
MgO	% d.b.	1.6	1.3	-
Na_2O	% d.b.	0.76	0.67	-
K_2O	% d.b.	1.7	1.6	-
Al_2O_3	% d.b.	20.6	18.8	-
Fe_2O_3	% d.b.	12.3	14.4	-
SiO_2	% d.b.	46.8	45.2	-
Calorific value (gross)	Btu/lb d.a.f.	14,550	15,490	-
Swelling No.		-	8	-
Gray King coke type		-	G9	-
Forms of sulphur				
Organic	% a.r.	-	1.2	-
Pyritic	% a.r.	-	1.45	-
Sulphate	% a.r.	-	0.07	-

Table A.1.1.3 Size distribution of coal

	% in grade by weight		
Test Series	1.1	1.2	1.3
Test No.	1.1	1.2-1.5	1.6-1.11
Particle Size (μm)			
+ 3175	0	0	0
+ 1680 - 3175	3.8	0.2	0.5
+ 1003 - 1680	16.7	11.9	11.3
+ 500 - 1003	30.0	34.4	27.1
+ 250 - 500	20.2	21.2	18.8
+ 125 - 250	11.9	12.9	13.2
+ 66 - 125	7.8	8.8	12.4
+ 45 - 66	3.6	3.1	6.8
- 45	5.9	7.5	9.9
Median dia. (μm)	508	456	337
Packed bulk density lb/ft^3	62.8	60.7	61.0

Table A.1.1.4 Chemical and size analyses of acceptor

Test Series	1.2 & 1.3
Test No.	1.2-1.11
Chemical Analysis	
CaO a.r.	45.9
MgO a.r.	0.94
CO_2 a.r.	34.7
SiO_2 a.r.	14.7
Size Analysis	% in grade by weight
Particle size (μm)	
+ 3175	0
+ 1680 - 3175	0.1
+ 1003 - 1680	5.9
+ 500 - 1003	15.1
+ 250 - 500	22.0
+ 125 - 250	22.5
+ 66 - 125	12.2
+ 45 - 66	5.0
- 45	17.2
Median diam. (μm)	20.7
Packed bulk density lb/ft^3	71.5

Table A.1.1.5. Chemical and size analyses of primary cyclone fines

Test Series	1.1	1.2				1.3					
Test No.	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	1.10	1.11
Chemical Analysis											
Carbon % a.r.	34.3	40.1	20.5	21.4	16.8	23.7	19.7	17.0	22.8	22.7	17.3
Sulphur % a.r.	1.25	1.3	2.8	2.45	3.0	2.8	2.95	2.85	2.85	2.7	2.45
Carbon dioxide % a.r.	0.25	0.47	4.1	7.74	5.3	2.48	4.34	5.1	3.01	5.63	7.34
CaO % a.r.	4.05	3.08	23.0	21.6	28.6	20.7	15.4	32.4	23.2	25.4	32.2
Size Analysis	% in grade by weight										
Particle size (μm)											
+ 3175	0	0	0	0	0	0	0	0	0	0	0
+ 1680 - 3175	0	0	0	0	0	0	0	0	0	0	0
+ 1003 - 1680	0	0	0	0	0	0	0	0	0	0	0
+ 500 - 1003	0.2	0.1	0	0	0	0	0	0	0	0.1	0.1
+ 250 - 500	9.7	7.0	8.4	7.1	7.2	7.9	6.7	7.4	6.9	2.2	3.2
+ 125 - 250	18.0	19.0	31.2	28.5	31.4	27.9	30.8	30.3	24.5	28.2	30.8
+ 66 - 125	24.5	27.4	21.3	21.2	20.9	25.4	22.5	20.9	25.8	27.4	27.0
+ 45 - 66	12.1	12.4	9.6	10.4	9.2	8.5	8.9	8.7	8.7	10.6	8.2
- 45	35.5	34.1	29.5	32.8	31.3	30.3	31.1	32.7	34.1	31.5	30.7
Median diam. (μm)	71	72	95	82	90	93	91	89	83	82	92
Packed bulk density lb/ft^3	39.9	40.6	49.7	51.3	56.9	48.6	41.8	56.9	51.0	55.7	57.1

Table A.1.1.6 Chemical analyses of secondary cyclone fines

Test Series	1.1	1.2				1.3					
Test No.	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	1.10	1.11
Analysis											
Carbon % a.r.	2.5	8.0	2.1	3.2	3.9	4.0	6.5	0.8	6.3	7.2	0.7
Sulphur "	1.5	1.3	6.55	6.2	6.1	4.9	5.0	6.2	5.4	5.0	5.25
CO_2 "	0.06	0.16	2.57	4.01	3.8	1.62	3.93	6.41	2.47	3.83	9.46
CaO "	3.78	3.04	17.9	19.7	22.4	25.7	23.4	29.0	19.2	17.2	29.4

Table A.1.1.7 Chemical analyses of exhust dust

Test Series	1.1	1.2				1.3					
Test No.	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	1.10	1.11
Analysis											
Carbon % a.r.	0.4	2.9	2.1	2.9	3.2	1.6	3.9	3.2	4.3	5.5	3.7
Sulphur "	2.6	4.7	5.9	5.6	5.9	6.7	6.75	7.5	5.1	5.55	6.45
CO_2 "	0.22	0.12	0.94	0.62	0.94	1.4	1.4	1.4	1.4	1.4	1.4
CaO "	2.94	2.8	11.3	13.7	15.7	7.3	18.8	22.8	16.2	15.7	23.8

Table A.1.1.8a Chemical and size analyses of bed material

Test Series	1.1			1.2						
Test No.	1.1			1.2		1.3		1.4		
Sample	Initial	Final	Offtake	Initial	Final	Initial	Final	Initial	Final	Offtake
Chemical Analysis										
Sulphur % a.r.	0.65	0.65	-	0.7	0.75	3.7	4.7	4.95	4.7	6.15
CO_2 % a.r.	0.11	0.11	-	0.12	0.13	0.3	0.38	8.11	10.94	0.91
CaO % a.r.	33.6	33.6	-	29.4	30.8	16.5	20.3	25.9	27.1	32.3
Size Analysis	% in grade by weight									
Particle size (μm)										
+ 3175	0.3	0.4	0.3	0.3	0.2	0.2	0.3	0	0.2	0
+ 1680 - 3175	1.3	1.6	1.3	1.1	1.3	1.2	1.0	0.7	1.8	0.4
+ 1003 - 1680	19.5	22.7	22.5	18.7	23.6	24.1	22.6	23.6	24.4	13.1
+ 500 - 1003	56.6	53.5	55.8	57.6	53.6	50.6	52.3	45.9	45.4	48.5
+ 250 - 500	22.0	21.4	19.3	22.3	21.3	23.6	23.4	28.9	27.6	36.9
+ 125 - 250	0.2	0.3	0.5	0	0	0.3	0.4	0.6	0.5	1.0
+ 66 - 125	0.1	0.1	0.2	0	0	0	0	0.1	0.1	0.1
+ 45 - 66		0	0.1	0	0	0	0	0.1	0	0
- 45		0	0	0	0	0	0	0.1	0	0
Median diam. (μm)	764	729	732	760	733	725	716	700	723	597
Packed bulk density lb/ft^3	82.9	80.6	85.6	94.9	82.5	92.1	83.3	97.1	90.9	57.5

Table A.1.1.8b Chemical and size analyses of bed material

Test Series	1.2			1.3							
Test No.	1.5			1.6		1.7			1.8		
Sample	Initial	Final	Offtake	Initial	Final	Initial	Final	Offtake	Initial	Final	Offtake
Chemical Analysis											
Sulphur % a.r.	5.6	6.2	5.3	2.15	2.6	3.65	4.05	3.5	4.55	5.15	4.8
CO_2 "	0.62	0.64	9.6	0.17	0.18	0.22	0.24	0.15	0.16	0.17	0.18
CaO "	31.8	33.4	29.3	10.2	12.5	18.0	22.3	17.2	23.2	26.6	24.4
Size Analysis	% in grade by weight										
Particle size (µm)											
+ 3175	0.1	0	0	0	0	0	0	0	0	0.1	0
+ 1680 - 3175	1.3	0.7	0.4	1.2	1.1	0.8	1.2	1.1	0.7	1.0	0.9
+ 1003 - 1680	20.8	24.2	14.7	25.4	24.9	21.8	24.0	20.0	20.5	22.5	20.4
+ 500 - 1003	49.9	44.3	49.2	46.3	44.1	45.7	42.6	45.0	43.2	41.4	37.4
+ 250 - 500	27.4	30.0	34.7	26.5	29.5	31.1	31.2	33.1	34.9	34.0	40.4
+ 125 - 250	0.5	0.6	0.9	0.5	0.4	0.5	0.7	0.7	0.7	0.7	0.9
+ 66 - 125	0	0.1	0.1	0.1	0	0.1	0.1	0.1	0	0.1	0
+ 45 - 66	0	0.1	0	0	0	0	0.1	0	0	0.1	0
- 45	0	0	0	0	0	0	0.1	0	0	0.1	0
Median diam. (µm)	714	689	621	736	701	673	674	647	628	639	570
Packed bulk density lb/ft^3	87.0	87.6	89.6	86.5	83.9	84.6	88.1	91.6	87.7	85.2	86.5

Table A.1.1.8c Chemical and size analyses of bed material

Test Series	1.3								
Test No.	1.9			1.10			1.11		
Sample	Initial	Final	Offtake	Initial	Final	Offtake	Initial	Final	Offtak
Chemical Analysis									
Sulphur % a.r.	5.9	5.8	6.85	1.75	2.6	2.0	4.25	4.6	-
CO_2 % a.r.	0.21	0.22	0.18	0.32	0.34	0.22	0.36	0.39	-
CaO % a.r.	26.0	26.0	28.8	9.65	13.9	9.8	22.3	23.8	-
Size Analysis	% in grade by weight								
Particle size (µm)									
+ 3175	0	0	0	0	0	0	0	0	0
+ 1680 - 3175	0.9	0.7	0.7	0.7	0.7	0.6	0.6	0.6	0.4
+ 1003 - 1680	20.0	20.2	15.4	21.9	21.1	19.7	17.3	19.5	14.9
+ 500 - 1003	44.4	42.0	39.3	44.9	44.8	43.6	42.9	40.5	39.4
+ 250 - 500	34.2	36.3	43.8	30.0	30.4	33.1	34.7	34.1	39.3
+ 125 - 250	0.5	0.6	0.8	2.5	3.0	3.0	4.5	5.2	5.9
+ 66 - 125	0	0.1	0	0	0	0	0	0.1	0.1
+ 45 - 66	0	0	0	0	0	0	0	0	0
- 45	0	0.1	0	0	0	0	0	0	0
Median diam. (µm)	637	612	539	670	660	627	594	596	537
Packed bulk density lb/ft^3	87.6	84.7	85.1	84.9	83.7	83.9	87.4	87.9	88.0

Table A.1.1.9a Flue gas analyses

Test No.		1.1				1.2				1.3		
Time from start (h)		1	1.75	3	Mean	0	1.5	3	Mean	1	3	Mean
Operating Conditions												
Ca/S mol ratio					0				0			2.2
Fluidising Velocity ft/s					4.0				4.0			4.0
Bed Temperature °F					1470				1470			1470
Bed Height ft					2.3				2.2			2.2
Gas Analysis	**Method**											
Vol % dry gas CO_2	Chromatograph	14.1	14.0	13.6	14.6	15.1	14.9	14.8	14.9	14.4	14.4	13.9
" O_2	"	4.0	4.0	4.2	4.1	3.3	3.4	3.3	3.3	4.1	4.5	4.3
" CO	"	0	0	0	0	0.02	0.02	0.02	0.02	0	0	0
" CH_4	"	0	0	0	0	0	0	0	0	0	0	0
p.p.m. SO_2	Iodine				1750				2050			400
" SO_2	I.R.A.				-				-			-
" SO_2	H_2O_2				-				1980			-
" Cl	"				-				72			-
" NH_3	"				-				3			-

Table A.1.1.9b Flue gas analyses

est No.		1.4				1.5		Datum	1.6			
ime from start (h)		0	1.5	2.5	Mean	3.5	Mean		0	2	3.75	Mean
Operating Conditions												
a/S mol ratio					2.2		2.2	0				1.3
luidising Velocity ft/s					4.0		4.0	4.0				4.0
ed Temperature °F					1380		1560	1560				1560
ed Height ft					2.2		2.2	2.2				2.2
Gas Analysis	**Method**											
vol % dry gas CO_2	Chromatograph	14.5	14.2	15.1	14.6	15.3	15.3	14.2	14.2	14.2	14.3	14.4
" O_2	"	3.8	4.3	3.3	3.8	3.4	3.4	4.0	4.5	4.4	3.9	4.2
" CO	"	0	0	0	0	0	0	0	0	0	0	0
" CH_4	"	0	0	0	0	0	0	0	0	0	0	0
.p.m. SO_2	Iodine				1020		360	2100				880
" SO_2	I.R.A.				–		360	–				780
" SO_2	H_2O_2				–		–	–				710
" Cl	"				–		–	–				61
" NH_3	"				–		–	–				0

Table A.1.1.9c Flue gas analyses

Test No.		1.7			1.8			1.9		
Time from start (h)		2	3.5	Mean	1.5	3	Mean	2	3.75	Mean
Operating Conditions										
Ca/S mol ratio				2.2			3.3			1.2
Fluidising Velocity ft/s				4.0			4.0			4.0
Bed Temperature °F				1560			1560			1560
Bed Height ft.				2.1			2.2			2.1
Gas Analysis	**Method**									
Vol % dry gas CO_2	Chromatograph	15.4	15.0	15.2	15.0	15.2	15.1	14.5	14.5	14.6
" O_2	"	2.9	3.3	3.1	3.3	3.3	3.3	2.8	2.5	2.6
" CO	"	0	0	0	0	0	0	0	0	0
" CH_4	"	0	0	0	0	0	0	0	0	0
p.p.m. SO_2	Iodine			510			180			840
" SO_2	I.R.A.			380			90			790
" SO_2	H_2O_2			500			160			550
" Cl	"			86			24			21
" NH_3	"			6			4			0

Table A.1.1.9d Flue gas analyses

Test No.		Datum	1.10					1.11		
Time from start (h)			0.5	1.5	2.5	3	Mean	0	1.5	Mean
Operating Conditions										
Ca/S mol ratio		0					2.2			3.3
Fluidising Velocity ft/s		3.0					3.0			3.0
Bed Temperature °F		1470					1470			1470
Bed Height ft		2.3					2.3			2.1
Gas Analysis	**Method**									
Vol % dry gas CO_2	Chromatograph	15.0	15.1	15.4	15.8	15.4	15.4	13.5	13.2	13.5
" O_2	"	2.6	2.8	2.8	2.8	3.2	3.0	2.6	3.3	2.9
" CO	"	0	0	0	0	0	0	0	0	0
" CH_4	"	0	0	0	0	0	0	0	0	0
p.p.m. SO_2	Iodine	2020					330			42
" SO_2	I.R.A.	-					315			25
" SO_2	H_2O_2	-					340			73
" Cl	"	-					49			32
" NH_3	"	-					2			2

Table A.1.1.10 Mass balance for Test 1.1

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium
Coal Feed	123.4	20.7	83.3	0	6.4	2.65	1.1
Acceptor Feed	0	0	0	0	0	0	0
Total Air	1300.4	0	0	999	301.4	0	0
Total Input	1423.8	20.7	83.3	999	307.8	2.65	1.1
Accumulated in bed	0	0	0	0	0	0	0
Offtake Ash	3.0	3.0	0	0	0	0.02	0.07
Primary Fines	18.9	12.4	6.48	0	0	0.24	0.55
Secondary Fines	1.3	1.3	0.03	0	0	0.02	0.04
Exhaust Dust	1.5	1.5	0.01	0	0	0.04	0.03
Flue Gas	1393.7	0	76.7	1003	306.0	2.42	0
Total Ouput	1418.4	18.1	83.2	1003	306.0	2.74	0.69
Loss (In-Out)	5.4	2.6	0.1	- 4	1.8	-0.09	0.41
Loss Percent	0.4	12.6	0.1	-0.4	0.6	-3.4	37.3

Excess air	15.4%	
Carbon loss	7.8%	(Unburnt)
Sulphur retention	9%	
Ca/S mol ratio	0	

Table A.1.1.11 Mass balance for Test 1.2

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium
Coal Feed	124.4	17.9	89.2	0	5.3	3.41	1.09
Acceptor Feed	0	0	0	0	0	0	0
Total Air	1300.4	0	0	999	301.5	0	0
Total Input	1424.8	17.9	89.2	999	306.8	3.41	1.09
Accumulated in bed	0	0	0	0	0	0.05	0.10
Offtake Ash	0	0	0	0	0	0	0
Primary Fines	19.3	11.5	7.72	0	0	0.25	0.42
Secondary Fines	0.9	0.8	0.07	0	0	0.01	0.02
Exhaust Dust	1.8	1.8	0.05	0	0	0.09	0.04
Flue Gas	1395.6	0	78.1	1006	302.4	2.81	0
Total Output	1417.6	14.1	85.9	1006	302.4	3.21	0.58
Loss (In - Out)	7.2	3.8	3.3	-7	4.4	0.20	0.51
Loss Percent	0.5	21.2	3.7	-0.7	1.4	5.9	47.3

Excess air	9.2%	
Carbon loss	9.2%	(Unburnt)
Sulphur retention	18%	
Ca/S mol ratio	0	

Table A.1.1.12 Mass balance for Test 1.3

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium
Coal Feed	116.5	16.8	83.5	0	5.0	3.19	1.02
Acceptor Feed	27.0	27.0	0	0	0	0	8.86
Total Air	1316.0	0	0	1011	305.0	0	0
Total Input	1459.5	43.8	83.5	1011	310	3.19	9.88
Accumulated in bed	0	0	0	0	0	0.79	2.14
Offtake Ash	14.0	14.0	0	0	0	0.59	1.84
Primary Fines	28.4	22.6	5.82	0	0	0.80	4.66
Secondary Fines	1.8	1.8	0.04	0	0	0.12	0.23
Exhaust Dust	2.3	2.2	0.05	0	0	0.13	0.18
Flue Gas	1408.6	0	76.4	1014	309.8	0.56	0
Total Ouput	1455.1	40.6	82.3	1014	309.8	2.98	9.05
Loss (In - Out)	4.4	3.2	1.2	- 3	0.2	0.21	0.83
Loss Percent	0.3	7.3	1.4	- 0.3	0.1	6.5	8.4

Excess air	17.4%	
Carbon loss	7.2%	(Unburnt)
Sulphur retention	83%	
Ca/S mol ratio	2.2	

Table A.1.1.13 Mass balance for Test 1.4

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium
Coal Feed	124.4	17.9	89.2	0	5.3	3.41	1.09
Acceptor Feed	28.3	28.3	0	0	0	0	9.29
Total Air	1377.2	0	0	1058	319.2	0	0
Total Input	1529.9	46.2	89.2	1058	324.5	3.41	10.38
Accumulated in bed	0	0	0	0	0	-0.26	0.95
Offtake Ash	12.2	12.2	0	0	0	0.59	2.32
Primary Fines	31.5	24.8	6.74	0	0	0.77	4.85
Secondary Fines	2.0	1.9	0.06	0	0	0.12	0.28
Exhaust Dust	1.6	1.6	0.05	0	0	0.09	0.16
Flue Gas	1475.8	0	81.1	1065	320.6	1.48	0
Total Output	1523.1	40.5	87.9	1065	320.6	2.80	8.56
Loss (In - Out)	6.8	5.7	1.3	-7	3.9	0.61	1.82
Loss Percent	0.4	12.3	1.4	0.7	1.2	17.9	17.5

Excess air	13.7%	
Carbon loss	7.8%	(Unburnt)
Sulphur retention	56%	
Ca/s mol ratio	2.2	

Table A.1.1.14 Mass balance for Test 1.5

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium
Coal Feed	111.5	16.1	80.0	0	4.8	3.06	0.98
Acceptor Feed	25.8	25.8	0	0	0	0	8.46
Total Air	1239.2	0	0	952	287.2	0	0
Total Input	1376.5	41.9	80.0	952	292	3.06	9.44
Accumulated in bed	0	0	0	0	0	0.57	1.15
Offtake Ash	12.0	12.0	0	0	0	0.71	2.80
Primary Fines	29.5	24.5	4.96	0	0	0.89	6.02
Secondary Fines	2.2	2.1	0.09	0	0	0.13	0.35
Exhaust Dust	0.8	0.8	0.03	0	0	0.05	0.09
Flue Gas	1332.0	0	76.4	955	292.4	0.47	0
Total Output	1376.5	39.4	81.5	955	292.4	2.82	10.40
Loss (In - Out)	0	2.5	-1.5	- 3	- 0.4	0.24	-0.96
Loss Percent	0	6.0	-1.9	-0.3	- 0.1	7.8	-10.1

Excess air	12.4%
Carbon loss	6.2% (Unburnt)
Sulphur retention	85%
Ca/S mol ratio	2.2

Table A.1.1.15 Mass Balance for Test 1.6

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium
Coal Feed	116.1	15.9	83.6	0	5.1	2.95	1.02
Acceptor Feed	14.1	14.1	0	0	0	0	4.63
Total Air	1254.8	0	0	964	290.8	0	0
Total Input	1385.0	30.0	83.6	964	295.9	2.95	5.65
Accumulated in bed	4.0	4.0	0	0	0	0.55	1.93
Offtake Ash	11.0	11.0	0	0	0	0.26	0.89
Primary Fines	25.0	19.1	5.92	0	0	0.70	3.70
Secondary Fines	1.4	1.3	0.06	0	0	0.07	0.29
Exhaust Dust	0.5	0.5	0.01	0	0	0.04	0.05
Flue Gas	1343.3	0	72.8	967	295.5	1.16	0
Total Output	1385.2	35.9	78.8	967	295.5	2.78	6.83
Loss (In - Out)	-0.2	-5.9	4.8	- 3	0.4	0.17	-1.18
Loss Percent	0	-19.7	5.8	-0.3	0.1	5.9	-20.9

Excess air	16.3%	
Carbon loss	7.6%	(Unburnt)
Sulphur retention	61%	
Ca/S mol ratio	1.3	

Table A.1.1.16 Mass balance for Test 1.7

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium
Coal Feed	121.0	16.6	87.1	0	5.3	3.07	1.07
Acceptor Feed	26.3	26.3	0	0	0	0	8.63
Total Air	1243.1	0	0	955	288.1	0	0
Total Input	1390.4	42.9	87.1	955	293.4	3.07	9.69
Accumulated in bed	0	0	0	0	0	0.45	3.37
Offtake Ash	12.0	12.0	0	0	0	0.46	1.73
Primary Fines	32.1	25.8	6.32	0	0	0.95	3.53
Secondary Fines	2.0	1.9	0.13	0	0	0.10	0.33
Exhaust Dust	0.6	0.5	0.02	0	0	0.04	0.07
Flue Gas	1335.2	0	76.0	960	290.7	0.67	0
Total Output	1381.9	40.2	82.5	960	290.7	2.66	9.04
Loss (In - Out)	8.5	2.7	4.6	-5	2.7	0.41	0.65
Loss Percent	0.6	6.3	5.3	-0.5	0.9	13.4	6.8

Excess air	9.2%	
Carbon loss	7.9%	(Unburnt)
Sulphur retention	78%	
Ca/s mol ratio	2.2	

Table A.1.1.17 Mass balance for Test 1.8

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium
Coal Feed	124.0	17.0	89.3	0	5.5	3.15	1.09
Acceptor Feed	39.0	39.0	0	0	0	0	12.79
Total Air	1254.8	0	0	964	290.8	0	0
Total Input	1417.8	56.0	89.3	964	296.2	3.15	13.88
Accumulated in bed	0	0	0	0	0	0.61	2.45
Offtake Ash	16.0	16.0	0	0	0	0.78	2.85
Primary Fines	38.0	31.5	6.46	0	0	1.08	8.78
Secondary Fines	1.5	1.5	0.01	0	0	0.09	0.31
Exhaust Dust	0.7	0.7	0.02	0	0	0.06	0.12
Flue Gas	1348.2		76.2	968	295.4	0.22	0
Total Output	1404.4	49.7	82.7	968	295.4	2.84	14.50
Loss (in - Out)	13.4	6.3	6.6	- 4	0.8	0.31	-0.62
Loss Percent	0.9	11.2	7.4	-0.4	0.3	9.7	-4.5

Excess air	10.3%	
Carbon loss	7.9%	(Unburnt)
Sulphur retention	93%	
Ca/S mol ratio	3.3	

Table A.1.1.18 Mass balance for Test 1.9

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium
Coal Feed	124.0	17.0	89.3	0	5.5	3.15	1.09
Acceptor Feed	14.1	14.1	0	0	0	0	4.62
Total Air	1244.3	0	0	956	288.3	0	0
Total Input	1382.4	31.1	89.3	956	293.8	3.15	5.72
Accumulated in bed	0	0	0	0	0	-0.11	0
Offtake Ash	9.0	9.0	0	0	0	0.53	1.67
Primary Fines	29.0	22.4	6.61	0	0	0.83	4.81
Secondary Fines	2.2	2.1	0.14	0	0	0.12	0.30
Exhaust Dust	1.5	1.4	0.06	0	0	0.08	0.17
Flue Gas	1334.4	0	73.0	957	295.9	1.10	0
Total Output	1376.1	34.9	79.8	957	295.9	2.55	6.95
Loss (In - Out)	6.3	-3.8	9.5	-1	-2.1	0.60	-1.23
Loss Percent	0.5	-12.2	10.6	-0.1	-0.7	19.0	-21.5

Excess air	13.8%	
Carbon loss	8.5%	(Unburnt)
Sulphur retention	65%	
Ca/S mol ratio	1.2	

Table A.1.1.19 Mass balance for Test 1.10

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium
Coal Feed	96.9	13.3	69.8	0	4.3	2.46	0.85
Acceptor Feed	20.6	20.6	0	0	0	0	6.76
Total Air	972.2	0	0	747	225.2	0	0
Total Input	1089.7	33.9	69.8	747	229.5	2.46	7.61
Accumulated in bed	0	0	0	0	0	0.99	3.49
Offtake Ash	15.0	15.0	0	0	0	0.33	1.26
Primary Fines	23.0	17.8	5.22	0	0	0.62	4.16
Secondary Fines	1.6	1.5	0.12	0	0	0.08	0.20
Exhaust Dust	1.0	1.0	0.06	0	0	0.06	0.11
Flue Gas	1045.2	0	60.2	749	229.1	0.34	0
Total Output	1085.8	35.3	65.6	749	229.1	2.42	9.22
Loss (In - Out)	3.9	-1.4	4.2	- 2	0.4	0.04	-1.61
Loss Percent	0.4	-4.1	6.0	-0.3	0.2	1.6	-21.2

Excess air	8.1%	
Carbon loss	8.2%	(Unburnt)
Sulphur retention	86%	
Ca/S mol ratio	2.2	

Table A.1.1.20 Mass balance for Test 1.11

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium
Coal Feed	94.5	12.9	68.0	0	4.2	2.4	0.83
Acceptor Feed	30.5	30.5	0	0	0	0	10.0
Total Air	1010.0	0	0	776	234.0	0	0
Total Input	1135.0	43.4	68.0	776	238.2	2.4	10.83
Accumulated in bed	0	0	0	0	0	0.37	1.15
Offtake Ash	17.0	17.0	0	0	0	0.75	2.8
Primary Fines	25.8	21.3	4.46	0	0	0.63	5.93
Secondary Fines	2.0	2.0	0.01	0	0	0.11	0.42
Exhaust Dust	1.4	1.4	0.05	0	0	0.09	0.24
Flue Gas	1085.1	0	62.6	781	234.9	0.08	0
Total Output	1131.3	41.7	67.2	781	234.9	2.03	10.54
Loss (In - Out)	3.7	1.7	0.8	-5	3.3	0.37	0.29
Loss Percent	0.3	3.9	1.2	-6	1.4	15.4	2.7

Excess air	9.2%	
Carbon loss	6.7%	(Unburnt)
Sulphur retention	97%	
Ca/S mol ratio	3.3	

Table A.1.1.21 Pressure drops through the combustor

Test Series	1.1	1.2			
Test No.	1.1	1.2	1.3	1.4	1.5
Fluidising Velocity ft/s	4.0	4.0	4.0	4.0	4.0
Bed Height ft	2.3	2.2	2.2	2.2	2.2
	Pressure drop, inches w.g.				
Baseplate	12.5	12	12	13	11
Bed	18.5	19	19	19.8	17.7
Density (over 8 in)	5.4	5.8	5.8	6	5.4
1° Cyclone	0.5	0.5	0.5	0	0.5
2° Cyclone	3	3	3	3.5	3.5

Test Series	1.3					
Test No.	1.6	1.7	1.8	1.9	1.10	1.11
Fluidising Velocity ft/s	4.0	4.0	4.0	4.0	3.0	3.1
Bed Height ft	2.2	2.1	2.2	2.1	2.3	2.1
	Pressure drop, inches w.g.					
Baseplate	10	10	10.5	10.5	7	7
Bed	20	19	19.5	19	20.5	20
Density (over 8 in)	6.1	6	5.9	6	5.9	6.3
1° Cyclone	0.5	0.5	1.0	1.0	0.5	0.5
2° Cyclone	3	3	3.5	3	1.5	2

Table A.1.1.22a Temperature distribution through the combustor

Test Series			1.1	1.2			
Test No.			1.1	1.2	1.3	1.4	1.5
Fluidising Velocity			4.0	4.0	4.0	4.0	4.0
Bed Height			2.3	2.2	2.2	2.2	2.2
Excess Air %			15.4	9.2	17.4	13.7	12.4
Probe Number	Height above bubble caps (ins)	Projection into combustor (ins)	Temperature °F				
N 2	4	3	1481	1477	1476	1386	1564
N14	4	9	1456	1485	1485	1393	1573
N 3	12	3	1492	1492	1490	1398	1576
N 4	12	9	1503	1499	1501	1409	1594
N15	12	3	1481	1474	1483	1384	1562
N 5	20	9	1490	1485	1486	1391	1571
N20	50	9	1528	1517	1526	1468	1602
N 9	94	9	1584	1562	1591	1560	1625
N23	94	9	1593	1560	1587	1558	1638
N10	130	9	1564	1508	1560	1555	1558
N25	130	9	1553	1510	1573	1567	1593
N11	154	9	1542	1477	1546	1551	1553
N26	154	9	1549	1477	1549	1553	1553
N27	154	9	1524	1461	1535	1537	1546
1° Cyclone			1395	1333	1391	1393	1389
2° Cyclone			1393	1333	1400	1418	1396
Steam to freeboard at N22 lb/h			0	0	0	0	100

Table A.1.1.22b Temperature distribution through the combustor

Test Series			1.3					
Test No.			1.6	1.7	1.8	1.9	1.10	1.11
Fluidising Velocity ft/s			4.0	4.0	4.0	4.0	3.0	3.1
Bed Height ft			2.2	2.1	2.2	2.1	2.3	2.1
Excess Air %			16.3	9.2	10.3	13.8	8.1	9.2
Probe Number	Height above bubble caps (ins)	Projection into combustor (ins)	Temperature °F					
N2	4	3	1558	1557	1558	1562	1474	1470
N14	4	9	1567	1571	1571	1569	1479	1476
N3	12	3	1573	1576	1575	1575	1486	1481
N4	12	9	1600	1600	1593	1598	1490	1483
N15	12	3	1562	1562	1562	1560	1476	1474
N5	20	9	1564	1566	1567	1567	1479	1476
N20	50	9	1593	1607	1609	1614	1524	1521
N9	94	9	1636	1629	1623	1623	1582	1582
N23	94	9	1634	1648	1652	1657	1582	1582
N10	130	9	1594	1571	1575	1580	1549	1555
N25	130	9	1602	1603	1600	1609	1564	1569
N11	154	9	-	-	-	-	-	-
N26	154	9	1569	1562	1564	1573	1531	1539
N27	154	9	1549	1553	1555	1562	1513	1521
1° Cyclone			1404	1400	1398	1400	1355	1360
2° Cyclone			1409	1409	1418	1409	1342	1362
Steam to freeboard at N22 lb/h			0	<100	<100	<100	0	0

Table A.1.1.23 SO_2 concentrations and % reductions

Test No.	1.1	1.2	1.3	1.4	1.5	Datum	1.6
Fluidising Velocity, ft/s	4	4	4	4	4	4	4
Bed Temperature, °F	1470	1470	1470	1380	1560	1560	1560
Ca/S mol ratio	0	0	2.2	2.2	2.2	0	1.3
SO_2 concentration, p.p.m.	1750	2050	400	1020	360	2100	880
SO_2 reduction, %	0	0	81	50	83	0	58

Test No.	1.7	1.8	1.9	Datum	1.10	1.11
Fluidising Velocity, ft/s	4	4	4	3	3	3
Bed Temperature, °F	1560	1560	1560	1470	1470	1470
Ca/S mol ratio	2.2	3.3	1.2	0	2.2	3.3
SO_2 concentration, p.p.m.	510	180	840	2020	330	42
SO_2 reduction, %	76	91	60	0	84	98

SO_2 reductions are based on a datum level of 2050 p.p.m.

A.1.2.1 Operating Conditions during Test Series 2

Coal	Pittsburg coal
Coal size	-3175 µm
Acceptor	Limestone 18
Bed Temperature	1560^{o}F
Recycle	No

Test No.		Datum	2.1	2.2	2.3	Datum	2.4	2.5
Time from start of Test Series (hrs)	Start	0	18	28	38	62	77	97
	End	5	22	32	42	64	81	99
Ca/S mol ratio		0	1.1	2.3	2.9	0	1.0	1.0
Coal Rate lb/h dry		258	258	258	258	128	128	96
Fluidising Velocity ft/s		8.1	8.1	8.1	8.0	4.0	4.0	3.0
Acceptor Size µm		-	-3175	-3175	-3175	-	-125	-125
Bed Height		2.1	2.1	2.1	2.1	2.1	2.1	2.0

Table A.1.2.2 Chemical analyses of coal

Test Number		2.2	2.4
Proximate analysis			
Total moisture	% a.r.	1.4	1.5
Ash	% a.r.	11.6	11.7
Volatile matter	% d.a.f.	41.5	-
Ultimate analysis			
Carbon	% d.b.	73.5	73.6
Hydrogen	% d.b.	4.6	4.7
Nitrogen	% d.b.	1.5	1.6
Sulphur	% d.b.	2.4	2.3
Oxygen + errors	% d.b.	5.0	4.7
Chlorine	% d.b.	0.06	0.08
Carbon Dioxide	% d.b.	0.5	0.5
Calorific value (gross)	Btu/lb d.a.f.	-	-
Swelling No.		8	8½
Gray King coke type		G9	G9

Additional samples of coal analysed for sulphur only

Test No.	2.1	2.2	2.3	2.4
Sulphur % d.b.	2.15	2.4	2.45	2.3

Table A.1.2.3 Size distribution of coal

	% in grade by weight			
Test No.	2.1	2.2	2.3	2.4
Particle Size (μm)				
+ 3175	0.6	0	0	0.3
+ 1680 - 3175	12.9	2.1	2.1	19.9
+ 1003 - 1680	14.4	8.1	9.6	19.4
+ 500 - 1003	23.7	20.9	24.6	23.9
+ 250 - 500	17.6	25.9	23.1	13.0
+ 125 - 250	11.4	16.8	15.9	8.1
+ 66 - 125	8.8	13.7	12.8	6.5
+ 45 - 66	4.6	6.6	7.3	2.2
- 45	6.0	5.9	4.6	6.7
Median diam. (μm)	526	309	337	763
Packed bulk density lb/ft^3	60.6	61.9	61.5	62.1

Table A.1.2.4 Chemical and size analyses of acceptor

Test No.	2.1-2.3	2.4
Chemical Analysis		
CaO a.r.	44.8	45.6
MgO "	0.86	0.86
CO_2 "	36.9	37.1
SiO_2 "	-	-
Size Analysis	% in grade by weight	
Particle size (μm)		
+ 3175	0	-
+ 1680 - 3175	11.1	-
+ 1003 - 1680	14.7	-
+ 500 - 1003	20.9	-
+ 250 - 500	20.0	-
+ 125 - 250	15.6	-
+ 66 - 125	7.1	-
+ 45 - 66	2.6	-
- 45	8.0	-
Median diam. (μm)	453	
Packed bulk density lb/ft^3	119.6	

Table A.1.2.5 Chemical and size analyses of primary cyclone fines

Test No.		2.1	2.2	2.3	2.4
Chemical Analysis					
Carbon	% a.r.	36.7	24.3	22.3	25.2
Sulphur	% a.r.	2.25	2.65	2.7	2.5
CO_2	% a.r.	2.1	4.36	4.25	4.37
CaO	% a.r.	17.5	28.2	32.8	28.6
Forms of Sulphur					
Organic	% a.r.	0.40	0.30	0.25	0.30
Pyritic	% a.r.	0.03	0.05	0.02	0.02
Sulphate	% a.r.	1.70	2.15	2.35	2.15
Size Analysis		% in grade by weight			
Particle size (μm)					
+ 3175		0	0	0	0
+ 1680	- 3175	0	0	0	0
+ 1003	- 1680	0.1	0	0	0
+ 500	- 1003	3.3	2.2	1.9	0.1
+ 250	- 500	12.6	12.3	11.9	4.2
+ 125	- 250	19.8	17.8	17.7	11.9
+ 66	- 125	23.6	20.7	19.4	26.4
+ 45	- 66	8.1	7.7	7.8	9.9
- 45		32.5	39.3	41.3	47.5
Median diam. (μm)		90	74	69	49
Packed bulk density lb/ft^3		43.2	54.4	55.3	44.8

Table A.1.2.6 Chemical analyses of secondary cyclone fines

Test No.	2.1	2.2	2.3	2.4
Analysis				
Carbon % a.r.	6.8	2.2	2.5	2.5
Sulphur % a.r.	3.7	7.15	5.75	6.1
CO_2 % a.r.	1.17	4.68	2.85	3.31
CaO % a.r.	14.3	31.6	28.4	34.7

Table A.1.2.7 Chemical analyses of exhaust dust

Test No.	2.1	2.2	2.3	2.4
Analysis				
Carbon % a.r.	4.0	4.1	2.8	2.8
Sulphur % a.r.	4.75	6.8	7.95	9.15
CO_2 % a.r.	1.05	1.05	1.05	1.05
CaO % a.r.	11.2	24.4	26.2	27.4

Table A.1.2.8 Chemical and size analyses of bed material

Test No.	2.1			2.2			2.3			2.4	
Sample	Initial	Final	Offtake	Initial	Final	Offtake	Initial	Final	Offtake	Initial	Final
Chemical Analysis											
Sulphur % a.r.	1.75	2.4*	1.25	2.8	3.4	2.0	3.55	4.1*	3.9	0.8	0.9
CO_2 % a.r.	0.44	0.45*	0.21	0.27	0.27	0.27	0.25	0.25*	0.25	0.12	0.16
CaO % a.r.	10.6	14.9*	7.8	16.6	20.2	12.2	21.5	22.9*	21.7	7.0	7.0
Size Analysis	% in grade by weight										
Particle size (μm)											
+ 3175	1.8		3.1	1.1	0.9	2.1	0.6		2.3	0.7	1.0
+ 1680 - 3175	42.1		43.6	32.8	29.6	42.9	33.2		32.8	26.8	27.3
+ 1003 - 1680	27.1		28.3	28.8	31.6	30.1	27.7		29.3	24.5	34.2
+ 500 - 1003	26.1		23.3	35.6	36.0	23.4	36.7		33.3	36.4	37.5
+ 250 - 500	2.2		1.6	1.5	1.1	1.1	1.6		2.1	11.6	0
+ 125 - 250	0.4		0.1	0.1	0.1	0.2	0.1		0.1	0	0
+ 66 - 125	0.1		0	0.1	0.1	0.1	0		0.1	0	0
+ 45 - 66	0.1		0	0	0.1	0	0		0	0	0
- 45	0.1		0	0	0.1	0.1	0.1		0	0	0
Median diam. (μm)	1516	-	1594	1243	1217	1556	1218	-	1286	1039	1211
Packed bulk density lb/ft^3	94.4		90.3	82.6	90.7	86.9	86.5		87.0	93.9	85.7

*Estimates

[illegible]

Test No.		Datum	2.1		2.2			2.3		
Time from start (h)			2	Mean	0.5	3	Mean	0.5	3.75	Mean
Operating Conditions										
Ca/S mol ratio		0		1.1			2.3			2.9
Fluidising Velocity ft/s		8.1		8.1			8.1			8.0
Bed Temperature °F		1560		1560			1560			1560
Bed Height ft.		2.1		2.1			2.1			2.1
Gas Analysis	**Method**									
Vol % dry gas CO_2	Chromatograph	15.5	15.2	15.2	14.9	14.5	14.7	16.1	16.2	16.1
" O_2	"	2.2	2.9	2.9	2.9	2.9	2.9	2.5	2.5	2.5
" CO	"	0	0	0	0	0	0	0	0	0
" CH_4	"	0	0	0	0	0	0	0	0	0
p.p.m. NO_X	Saltzman's	443 404	467 471	470	533	497	515			-
" SO_2	Iodine	1830		1200			900			650
" SO_2	I.R.A.	-		900			650			475
" SO_2	H_2O_2	-		1240			860			680
" Cl	"			23			30			40
" NH_3	"	-		4			4			0

Table A.1.2.9b Flue gas analyses

Test No.		Datum	2.4				2.5		
Time from start (h)			1.5	2.5	3	Mean			Mean
Operating Conditions									
Ca/S mol ratio		0				1.0			1.0
Fluidising Velocity ft/s		4.0				4.0			3.0
Bed Temperature °F		1560				1560			1560
Bed Height		2.1				2.1			2
Gas Analysis	Method								
Vol % dry gas CO_2	Chromatograph	15.2	15.1	15.2	15.6	15.0	16.6	16.3	16.4
" O_2	"	3.0	3.1	3.0	2.7	3.2	2.5	2.8	2.6
" CO	"	-	0	0	0	0	0	0	0
" CH_4	"	-	0	0	0	0	0	0	0
p.p.m. NO_X	Saltzman's	-				-			-
" SO_2	Iodine	2100				1050			1050
" SO_2	I.R.A.	1850				990			-
" SO_2	H_2O_2	-				890			-
" Cl	"	-				20			-
" NH_3	"	-				0			-

Table A.1.2.10 Mass balance for Test 2.1

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium
Coal Feed	258.3	30.0	190.4	0	12.9	5.68	2.27
Acceptor Feed	24.1	24.1	0	0	0	0	7.86
Total Air	2525.1	0	0	1940	585.1	0	0
Total Input	2807.5	54.1	190.4	1940	598.0	5.68	10.13
Accumulated in bed	0	0	0	0	0	0.56	2.56
Offtake Ash	9.0	9.0	0	0	0	0.19	0.82
Primary Fines	64.5	40.8	23.67	0	0	1.45	8.06
Secondary Fines	4.0	3.7	0.27	0	0	0.15	0.41
Exhaust Dust	2.1	2.0	0.08	0	0	0.10	0.17
Flue Gas	2713.9	0	154.1	1952	590.2	3.19	0
Total Output	2793.5	55.5	178.1	1952	590.2	5.64	12.02
Loss (In - Out)	14.0	-1.4	12.3	-12	7.8	0.04	-1.89
Loss Percent	0.5	-2.6	6.5	-6.2	1.3	0.7	-18.7

Excess air	2.5%	
Carbon loss	13.5%	(Unburnt)
Sulphur retention	44%	
Ca/S mol ratio	1.1	

Table A.1.2.11 Mass balance for Test 2.2

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium
Coal Feed	258.3	30.0	190.4	0	12.9	6.2	2.27
Acceptor Feed	54.0	54.0	0	0	0	0	17.60
Total Air	2517.3	0	0	1934	583.3	0	0
Total Input	2829.6	84.0	190.4	1934	596.2	6.2	19.88
Accumulated in bed	0	0	0	0	0	0.45	1.86
Offtake Ash	11.4	11.4	0	0	0	0.35	1.50
Primary Fines	86.0	65.1	20.9	0	0	2.28	17.37
Secondary Fines	3.4	3.3	0.07	0	0	0.24	0.77
Exhaust Dust	2.8	2.7	0.12	0	0	0.19	0.49
Flue Gas	2699.5	0	148.6	1957	575.7	2.38	0
Total Output	2803.1	82.5	169.7	1957	575.7	5.89	21.99
Loss (In - Out)	26.5	1.5	20.7	-23	20.5	0.31	-2.11
Loss Percent	0.9	1.7	10.9	-1.2	3.4	4.9	-10.6

Excess air	4.1%	
Carbon loss	12.4%	(Unburnt)
Sulphur retention	62%	
Ca/S mol ratio	2.3	

Table A.1.2.12 Mass balance for Test 2.3

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium
Coal Feed	258.3	30.0	190.4	0	12.9	6.46	2.27
Acceptor Feed	72.0	72.0	0	0	0	0	23.47
Total Air	2509.6	0	0	1928	581.6	0	0
Total Input	2839.9	102.0	190.4	1928	594.5	6.46	25.74
Accumulated in bed	0	0	0	0	0	0.42	0.76
Offtake Ash	14.0	14.0	0	0	0	0.54	2.23
Primary Fines	100.0	77.7	22.30	0	0	2.70	23.50
Secondary Fines	4.0	3.9	0.10	0	0	0.23	0.81
Exhaust Dust	2.1	2.0	0.06	0	0	0.17	0.39
Flue Gas	2710.0	0	162.2	1928	601.4	1.71	0
Total Ouput	2830.1	97.6	184.7	1928	601.4	5.77	27.69
Loss (In - Out)	9.8	4.4	5.7	0	- 6.9	0.69	-1.95
Loss Percent	0.3	4.2	3.0	0	- 1.2	10.7	-7.6

Excess air	1.3%	
Carbon loss	12.2%	(Unburnt)
Sulphur retention	73%	
Ca/S mol ratio	2.9	

Table A.1.2.13 Mass balance for Test 2.4

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium
Coal Feed	128.2	14.9	94.5	0	6.4	3.01	1.13
Acceptor Feed	12.0	12.0	0	0	0	0	3.84
Total Air	1262.6	0	0	970	292.6	0	0
Total Input	1402.8	26.9	94.5	970	299.0	3.01	4.97
Accumulated in bed	0	0	0	0	0	0.10	0
Offtake Ash	4.0	4.0	0	0	0	0.03	0.20
Primary Fines	27.1	20.3	6.83	0	0	0.68	5.53
Secondary Fines	3.4	3.3	0.09	0	0	0.21	0.84
Exhaust Dust	1.3	1.3	0.04	0	0	0.12	0.26
Flue Gas	1356.3	0	76.1	975	296.3	1.39	0
Total Output	1392.1	28.9	83.0	975	296.3	2.53	6.83
Loss (In - Out)	10.7	-2.0	11.5	-5	2.7	0.48	-1.86
Loss Percent	0.8	-7.4	12.1	-0.5	0.9	15.9	-37.4

Excess air	9.3%	
Carbon loss	8.4%	(Unburnt)
Sulphur retention	54%	
Ca/S mol ratio	1.0	

Table A.1.2.14 Pressure drops through the combustor

Test No.	2.1	2.2	2.3	2.4
Fluidising Velocity ft/s	8.1	8.1	8.0	4.0
Bed Height ft.	2.1	2.1	2.1	2.1
	Pressure drop, inches w.g.			
Baseplate	40	40	40	12
Bed	14.5	14	13.5	18.5
Density (over 8 in.)	4.6	4.4	4.3	5.9
1° Cyclone	2.5	2.5	2.5	0.5
2° Cyclone	17	17	17.5	4

Table A.1.2.15 Temperature distribution through the combustor

Test No.			2.1	2.2	2.3	2.4
Fluidising Velocity ft/s			8.1	8.1	8.0	4.0
Bed Height ft			2.1	2.1	2.1	2.1
Excess Air %			2.5	4.1	1.3	9.3
Probe Number	Height above bubble caps (ins)	Projection into combustor (ins)	Temperature °F			
N2	4	3	1551	1551	1548	1567
N14	4	9	1578	1585	1580	1578
N3	12	3	1589	1589	1584	1591
N4	12	9	1638	1627	1630	1589
N15	12	3	1564	1527	1564	1562
N5	20	9	1584	1580	1558	1573
N20	50	9	1634	1638	1634	1659
N9	94	9	1391	1411	1427	1522
N23	94	9	1605	1634	1632	1688
N10	130	9	1596	1616	1629	1594
N25	130	9	1544	1567	1580	1600
N11	154	9	1596	1603	1611	1602
N26	154	9	1580	1607	1618	1596
N27	154	9	1537	1558	1567	1566
1° Cyclone			1429	1447	1449	1391
2° Cyclone			1465	1481	1485	1420
Steam to freeboard at N22. lb/h			440	420	440	200-100

Table A.1.2.16 SO_2 concentrations and % reductions

Test No.	Datum	2.1	2.2	2.3	Datum	2.4	2.5
Fluidising Velocity, ft/s	8	8	8	8	4	4	3
Bed Temperature, °F	1560	1560	1560	1560	1560	1560	1560
Acceptor size, μm	-	-3175	-3175	-3175	-	-125	-125
Ca/S mol ratio	0	1.1	2.3	2.9	0	1.0	1.0
SO_2 concentration, p.p.m.	1830	1200	900	650	2100	1050	1050
SO_2 reduction, %	0	34	56	68	0	49	49

The low datum concentration before Test 2.1 was due to the low sulphur content of the coal, Table A.1.2.2. This was used only for Test 2.1. The datum for the other tests was taken as 2050 p.p.m.

Table A.1.3.1 Operating Conditions during Test Series 3

Coal	Welbeck coal
Coal size (upper limit)	3175 μm
Acceptor	U.K. Limestone
Acceptor size (upper limit)	3175 μm
Fines Recycle	System not in operation

Test No.		3.1	3.2	3.3	3.4	Temperature Survey	3.5	3.6
Time from start of Test Series (hrs)	Start	22	55	76	86	90	96	104
	End	26	59	80	90	91	99	107
Ca/s mol ratio		0	1.8	2.1	2.8	2.8	2.8	3.0
Coal Rate lb/hr. dry		303	293	301	301	301	312	152
Fluidising Velocity ft/s		7.9	8.0	8.0	7.9	8.3-7.7	8.0	4.1
Bed height ft		2.1	2.1	2.1	2.2	2.2	3.7-3.9	2.2-2.4
Bed Temperature ^{o}F		1560	1560	1560	1560	1630-1470	1560	1560

Table A.1.3.2 Chemical analyses of coal

Test Number		3.1	3.5
Proximate analysis			
Total moisture	% a.r.	3.3	3.5
Ash	% a.r.	24.5	25.9
Volatile matter	% d.a.f.	38.0	-
Ultimate analysis			
Carbon	% d.b.	61.7	60.0
Hydrogen	% d.b.	3.6	3.4
Nitrogen	% d.b.	1.3	1.4
Sulphur	% d.b.	1.45	1.4
Oxygen + errors	% d.b.	4.4	4.0
Chlorine	% d.b.	0.62	0.57
Carbon Dioxide	% d.b.	1.21	1.03
Ash analysis			
CaO	% d.b.	4.9	3.2
MgO	% d.b.	1.96	2.0
Na_2O	% d.b.	1.8	1.76
K_2O	% d.b.	3.1	3.2
Al_2O_3	% d.b.	19.3	19.4
Fe_2O_3	% d.b.	8.2	8.3
SiO_2	% d.b.	54.2	56.2
Calorific value (gross)	Btu/lb d.a.f.	14,100	-
Swelling No.		1	-
Gray King coke type		C	-
Forms of Sulphur			
Organic	% a.r.	0.73	0.67
Pyritic	% a.r.	0.65	0.65
Sulphate	% a.r.	0.03	0.02

Additional samples of coal analysed for sulphur only

Test No.	3.1	3.2	3.5	3.6
Sulphur % d.b.	1.45	1.4	1.4	1.4

Table A.1.3.3. Size distribution of coal

	% in grade by weight				
Test No.	3.1	3.2	3.3	3.5	3.6
Particle Size (μm)					
+ 3175	0.1	0.1	0	0.1	0.3
+ 1680 - 3175	12.6	15.3	25.9	24.7	24.8
+ 1003 - 1680	17.2	18.1	20.2	22.6	22.6
+ 500 - 1003	24.2	20.0	18.2	18.7	22.2
+ 250 - 500	16.2	14.7	9.7	10.3	8.9
+ 125 - 250	9.5	9.2	6.3	6.4	4.8
+ 66 - 125	7.0	7.3	5.9	5.4	4.6
+ 45 - 66	2.6	3.4	2.7	2.5	2.0
- 45	10.6	11.9	11.1	9.9	9.8
Median diam. (μm)	571	569	889	929	946
Packed bulk density lb/ft^3	60	63.1	58	56.8	65.9

Table A.1.3.4 Chemical and size analyses of acceptor

Test No.	3.4	3.5
Chemical Analysis		
CaO a.r.	55.5	55.4
MgO "	0.28	0.28
CO_2 "	43.8	43.7
SiO_2 "	-	-
Size Analysis	% in grade by weight	
Particle size (μm)		
+ 3175	0	0
+ 1680 - 3175	11.1	6.8
+ 1003 - 1680	13.9	12.4
+ 500 - 1003	16.3	20.4
+ 250 - 500	22.7	27.8
+ 125 - 250	14.2	14.3
+ 66 - 125	8.2	18.3
+ 45 - 66	2.9	2.3
- 45	10.7	7.7
Median diam. (μm)	391	316

Table A.1.3.5 Chemical and size analyses of primary cyclone fines

Test No.	3.1	3.2	3.3	3.4	3.5	3.6
Chemical Analysis						
Carbon % a.r.	23.6	18.9	16.3	18.3	18.5	15.5
Sulphur % a.r.	0.4	1.1	1.2	1.25	1.6	1.95
CO_2 % a.r.	0.4	2.59	12.3	3.9	4.29	4.5
CaO % a.r.	3.08	14.3	17.2	17.5	18.8	20.0
Forms of Sulphur						
Organic % a.r.	-	-	-	0.15	0.15	-
Pyritic % a.r.	-	-	-	0.06	0.07	-
Sulphate % a.r.	-	-	-	1.10	1.35	-
Size Analysis	% in grade by weight					
Particle size (μm)						
+ 3175	0	0	0	0	0	0
+ 1680 - 3175	0	0	0	0	0	0
+ 1003 - 1680	0.1	0	0	0	0.2	0
+ 500 - 1003	8.7	6.1	5.2	6.6	8.4	0.4
+ 250 - 500	24.7	20.9	19.7	17.3	20.2	13.7
+ 125 - 250	17.3	18.2	17.9	15.9	13.0	25.5
+ 66 - 125	15.4	18.1	17.9	18.4	17.8	19.9
+ 45 - 66	5.8	6.4	6.7	7.7	6.3	6.9
- 45	28.0	30.3	32.6	34.1	29.1	33.6
Median diam. (μm)	129	107	99	90	113	94
Packed bulk density lb/ft^3	45.3	53.9	52.5	49.7	51.6	46.3

Table A.1.3.6 Chemical analyses of secondary cyclone fines

Test No.	3.1	3.2	3.3	3.4	3.5	3.6
Analysis						
Carbon % a.r.	13.8	6.9	7.6	7.8	8.6	7.9
Sulphur "	0.35	2.3	2.35	2.25	2.6	2.45
CO_2 "	0.08	0.23	0.25	0.46	0.34	0.45
CaO "	2.7	9.9	11.8	10.5	11.6	10.8

Table A.1.3.7 Chemical analyses of exhaust dust

Test No.	3.1	3.2	3.3	3.4	3.5	3.6
Analysis						
Carbon % a.r.	1.25	4.3	6.7	6.7	6.7	6.7
Sulphur "	0.5	2.3	2.35	2.25	2.6	2.45
CO_2 "	0.2	0.23	0.25	0.46	0.34	0.45
CaO "	14.9	10.7	11.4	10.5	3.2	3.2

Table A.1.3.8a Chemical and size analyses of bed material

Test No.	3.1		3.2			3.3			3.4		
Sample	Initial	Final	Initial	Final	Offtake	Initial	Final	Offtake	Initial	Final	Offtake
Chemical Analysis											
Sulphur % a.r.	0.3	0.55	1.0	1.15	1.2	1.25	1.7	2.0	1.7	2.15	-
CO_2 % a.r.	0.18	0.18	0.18	0.22	0.2	0.02	0.16	0.22	0.28	0.22	-
CaO % a.r.	3.5	4.6	8.4	9.9	10.3	10.2	13.0	15.1	12.9	16.1	-
Size Analysis	% in grade by weight										
Particle size (μm)											
+ 3175	0.1	0.2	0.4	0.1	0	-	-	0	0	0	0.3
+ 1680 - 3175	16.9	13.9	17.7	13.4	26.9	-	-	21.5	15.5	12.9	22.3
+ 1003 - 1680	28.5	29.4	24.4	28.7	29.8	-	-	27.7	28.7	27.6	28.8
+ 500 - 1003	48.2	49.3	51.9	52.4	39.7	-	-	47.7	52.8	55.8	44.5
+ 250 - 500	6.0	7.1	5.6	5.3	3.3	-	-	2.7	2.9	3.1	3.7
+ 125 - 250	0.1	0.1	0	0.1	0.2	-	-	0.2	0.1	0.3	0.2
+ 66 - 125	0.1	0	0	0	0.1	-	-	0.1	0	0.1	0.1
+ 45 - 66	0.1	0	0	0	0	-	-	0	0	0.1	0.1
- 45	0	0	0	0	0	-	-	0.1	0	0.1	0
Median diam. (μm)	944	920	909	909	1113	-	-	992	932	894	1024
Packed bulk density lb/ft^3	78.3	79.0	83.7	77.2	77.7	-	-	79.7	73.9	78.1	79.6

Table A.1.3.8b Chemical and size analysis of bed material

Test No.	3.5			3.6			Newdigate Shale
Sample	Initial	Final	Offtake	Initial	Final	Offtake	
Chemical Analysis							
Sulphur % a.r.	1.7	2.1	2.15	2.1	2.2	2.15	-
CO_2 "	0.19	0.25	0.25	0.17	0.11	0.19	-
CaO "	12.5	15.2	15.2	12.7	13.2	12.7	0.91
MgO "	-	-	-	-	-	-	1.12
Size Analysis	% in grade by weight						
Particle size (μm)							
+ 3175	0	0.1	0.2	0	0.1	0.2	
+ 1680 - 3175	22.0	18.8	23.8	16.3	14.2	22.4	
+ 1003 - 1680	30.8	31.0	30.9	28.5	25.9	28.1	
+ 500 - 1003	45.3	48.1	41.4	46.6	47.6	43.6	
+ 250 - 500	1.7	1.6	3.4	8.1	11.8	5.4	
+ 125 - 250	0.1	0.1	0.2	0.2	0.1	0.2	
+ 66 - 125	0.1	0.1	0.1	0.1	0.1	0.1	
+ 45 - 66	0	0.1	0	0.1	0.1	0	
- 45	0	0.1	0	0.1	0.1	0	
Median diam. (μm)	1043	1002	1079	933	875	1013	
Packed bulk density lb/ft^3	74.6	80.4	78.9	78.0	61.1	79.1	

Table A.1.3.9a Flue gas analyses

Test No.		3.1			3.2			3.3			
Time from start (h)		1	3	Mean	1.5	3	Mean	1	1.5	3.5	Mean
Operating Conditions											
Ca/S mol ratio				0			1.8				2.1
Fluidising Velocity, ft/s				7.9			8.0				8.0
Bed Temperature ^{o}F				1560			1560				1560
Bed Height, ft				2.1			2.1				2.2
Gas Analysis	**Method**										
Vol % dry gas CO_2	Chromatograph	15.2	15.2	15.2	15.6	15.4	15.5	14.1	15.1	15.0	15.0
" O_2	"	2.7	3.0	2.9	2.8	3.1	3.0	4.4	3.5	3.3	3.4
" CO	"	0	0	0	0	0	0	0	0	0	0
" CH_4	"	0	0	0	0	0	0	0	0	0	0
" SO_2	Iodine			1480			910				740
" SO_2	I.R.A.			1430			850				590
" SO_2	H_2O_2			1475			980				630
" Cl^-	"			430			565				455
" NH_3	"			11			8.5				8

Table A.1.3.9b Flue gas analyses

Test No.		3.4				3.5		3.6		
Time from start (h)		2	2.5	3.5	Mean	2	Mean	0.5	2.5	Mean
Operating Conditions										
Ca/S mol ratio					2.8		2.8			3.0
Fluidising Velocity ft/s					7.9		8.0			4.1
Bed Temperature °F					1560		1560			1560
Bed Height ft.					2.2		3.8			2.3
Gas Analysis	Method									
Vol % dry gas CO_2	Chromatograph	14.9	15.2	14.9	15.0	15.2	15.2	16.0	16.1	16.0
" O_2	"	3.4	3.2	3.4	3.4	3.3	3.3	3.6	3.0	3.1
" CO	"	0	0	0	0	0	0	0	0	0
" CH_4	"	0	0	0	0	0	0	0	0	0
p.p.m. SO_2	Iodine				540		540			420
" SO_2	I.R.A.				420		420			280
" SO_2	H_2O_2				465		580			390
" Cl	"				380		455			410
" NH_3	"				11.5		13			10

Table A.1.3.10 Mass balance for Test 3.1

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium
Coal Feed	303.0	73.9	187.0	0	13.3	4.39	2.79
Acceptor Feed	0	0	0	0	0	0	0
Total Air	2463.9	0	0	1893	570.9	0	0
Total Input	2766.9	73.9	187.0	1893	584.2	4.39	2.79
Accumulated in bed	0	0	0	0	0	0.12	0.39
Offtake Ash	27.5	27.5	0	0	0	0.12	0.80
Primary Fines	76.5	58.4	18.05	0	0	0.31	1.68
Secondary Fines	2.5	2.2	0.35	0	0	0.01	0.05
Exhaust Dust	2.1	2.0	0.03	0	0	0	0.22
Flue Gas	2644.9	0	150.8	1909	570.2	3.76	0
Total Output	2753.5	90.1	169.2	1909	570.2	4.32	3.14
Loss (In - Out)	13.4	-16.2	17.8	-16	14.0	0.07	-0.35
Loss Percent	0.5	-21.9	9.5	-0.9	2.4	1.7	-12.6

Excess air	5.2%	
Carbon loss	10.9%	(Unburnt)
Sulphur retention	14%	
Ca/S mol ratio	0	

Table A.1.3.11 Mass balance for Test 3.2

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium
Coal Feed	293.4	71.6	181.0	0	12.9	4.25	2.70
Acceptor Feed	23.8	23.8	0	0	0	0	9.45
Total Air	2501.8	0	0	1922	579.8	0	0
Total Input	2819.0	95.4	181.0	1922	592.7	4.25	12.15
Accumulated in bed	0	0	0	0	0	0.09	0.69
Offtake Ash	33.5	33.5	0	0	0	0.36	2.19
Primary Fines	86.5	70.2	16.35	0	0	0.95	8.82
Secondary Fines	3.0	2.8	0.21	0	0	0.07	0.21
Exhaust Dust	2.1	2.0	0.09	0	0	0.05	0.16
Flue Gas	2688.1	0	155.3	1932	586.1	2.32	0
Total Output	2813.2	108.5	172.0	1932	586.1	3.84	12.07
Loss (In - Out)	5.8	-13.1	9.0	- 10	6.6	0.41	0.08
Loss Percent	0.2	-13.7	5.0	-0.5	1.1	9.6	0.7

Excess air	7.3%	
Carbon loss	9.7%	(Unburnt)
Sulphur retention	45%	
Ca/S mol ratio	1.8	

Table A.1.3.12 Mass balance for Test 3.3

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium
Coal Feed	301.1	73.5	185.8	0	13.2	4.06	2.77
Acceptor Feed	26.4	26.4	0	0	0	0	10.48
Total Air	2497.9	0	0	1919	578.9	0	0
Total Input	2825.4	99.9	185.8	1919	592.1	4.06	13.25
Accumulated in bed	0	0	0	0	0	0.23	1.04
Offtake Ash	21.0	21.0	0	0	0	0.31	1.74
Primary Fines	91.0	76.2	14.83	0	0	1.09	11.19
Secondary Fines	3.5	3.2	0.27	0	0	0.08	0.29
Exhaust Dust	2.1	2.0	0.14	0	0	0.05	0.17
Flue Gas	2680.5	0	150.9	1930	584.6	1.90	0
Total Output	2798.1	102.4	166.2	1930	584.6	3.66	14.43
Loss (In - Out)	27.3	-2.5	19.6	-11	7.5	0.40	-1.18
Loss Percent	1.0	-2.5	10.5	-0.5	1.3	9.9	-9.0

Excess air	9.7%	
Carbon loss	9.2%	(Unburnt)
Sulphur retention	53%	
Ca/S mol ratio	2.1	

Table A.1.3.13 Mass balance for Test 3.4

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium
Coal Feed	301.1	73.5	185.8	0	13.2	4.06	2.77
Acceptor Feed	36.4	36.4	0	0	0	0	14.45
Total Air	2471.7	0	0	1899	572.7	0	0
Total Input	2809.2	109.9	185.8	1899	585.9	4.06	17.22
Accumulated in bed	0	0	0	0	0	0.47	2.41
Offtake Ash	21.0	21.0	0	0	0	0.40	2.17
Primary Fines	108.0	88.2	19.76	0	0	1.35	13.50
Secondary Fines	4.0	3.7	0.31	0	0	0.09	0.30
Exhaust Dust	2.1	1.9	0.14	0	0	0.05	0.16
Flue Gas	2651.5	0	149.3	1908	579.2	1.42	0
Total Output	2786.6	114.8	169.5	1908	579.2	3.78	18.54
Loss (In - Out)	22.6	- 4.9	16.3	-9	6.7	0.28	-1.32
Loss Percent	0.8	- 4.4	8.8	-0.5	1.2	6.9	-7.6

Excess air	6.9%	
Carbon loss	11.9%	(Unburnt)
Sulphur retention	65%	
Ca/S mol ratio	2.8	

Table A.1.3.14 Mass balance for Test 3.5

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium
Coal Feed	311.7	83.5	187.0	0	12.5	4.36	2.87
Acceptor Feed	39.0	39.0	0	0	0	0	15.48
Total Air	2486.3	0	0	1910	576.3	0	0
Total Input	2837.0	122.5	187.0	1910	588.8	4.36	18.35
Accumulated in bed	5.0	5.0	0	0	0	0.79	3.96
Offtake Ash	19.5	19.5	0	0	0	0.37	1.93
Primary Fines	112.5	91.7	20.81	0	0	1.80	15.07
Secondary Fines	5.1	4.7	0.44	0	0	0.13	0.42
Exhaust Dust	2.1	2.0	0.14	0	0	0.05	0.05
Flue Gas	2669.9	0	152.3	1919	583.4	1.42	0
Total Output	2814.1	122.9	173.7	1919	583.4	4.56	21.43
Loss (In - Out)	22.9	-0.4	13.3	-9	5.4	-0.2	-3.08
Loss Percent	0.8	-0.3	7.1	-0.5	0.9	-4.5	-16.8

Excess air	5.8%	
Carbon loss	12.3%	(Unburnt)
Sulphur retention	68%	
Ca/S mol ratio	2.8	

Table A.1.3.15 Mass balance for Test 3.6

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium
Coal Feed	151.5	40.6	90.9	0	6.1	2.12	1.39
Acceptor Feed	20.0	20.0	0	0	0	0	7.94
Total Air	1278.1	0	0	982	296.1	0	0
Total Input	1449.6	60.6	90.9	982	302.2	2.12	9.22
Accumulated in bed	0	0	0	0	0	0.24	0.84
Offtake Ash	20.0	20.0	0	0	0	0.43	1.85
Primary Fines	33.0	27.9	5.11	0	0	0.64	4.72
Secondary Fines	3.0	2.8	0.24	0	0	0.07	0.23
Exhaust Dust	1.1	1.0	0.07	0	0	0.03	0.02
Flue Gas	1375.6	0	82.5	980	305.9	0.57	0
Total Output	1432.7	51.7	87.9	980	305.9	1.98	7.66
Loss (In - Out)	16.9	8.9	3.0	2	- 3.7	0.14	1.67
Loss Percent	1.1	14.8	3.3	0.2	- 1.2	6.9	17.9

Excess air	10.4%	
Carbon loss	6.2%	(Unburnt)
Sulphur retention	73%	
Ca/S mol ratio	3.0	

Table A.1.3.16 Pressure drops through the combustor

Test No.	3.1	3.2	3.3	3.4	3.5	3.6
Fluidising Velocity ft/s	7.9	8.0	8.0	7.9	8.0	4.1
Bed Height ft	2.1	2.1	2.1	2.2	3.75-3.9	2.2-2.4
	Pressure drop, inches w.g.					
Base plate	38	36.5	36	35	35	12.5
Bed	12	12	12	12.5	24	19
Density (over 8 in)	3.8	3.8	3.8	3.8	4.3-4.1	5.8-5.3
1^{o} Cyclone	2.5	2.5	3	3	2.5	1
2^{o} Cyclone	13.5	14	15	15	13	3

Table A.1.3.17 Temperature distribution through the combustor

APCO Test No.			3.1	3.2	3.3	3.4	3.5	3.6
Fluidising Velocity			7.9	8.0	8.0	7.9	8.0	4.1
Bed Height			2.1	2.1	2.1	2.2	3.7 - 3.4	2.2 - 2.4
Excess Air %			5.2	7.3	9.7	6.9	5.8	10.4
Probe Number	Height above bubble caps (ins)	Projection into combustion (ins)	Temperature °F					
N 2	4	3	1567	1557	1539	1540	1540	1557
N14	4	9	1584	1575	1558	1564	1558	1562
N 3	12	3	1585	1584	1562	1573	1575	1573
N 4	12	9	1585	1557	1537	1544	1540	1548
N15	12	3	1567	1571	1557	1566	1571	1555
N 5	20	9	1593	1587	1582	1591	1584	1578
N20	50	9	1634	1636	1648	1647	1611	1632
N 9	94	9	1441	1429	1539	1350	1494	1589
N23	94	9	1650	1636	1648	1458	1578	1656
N10	130	9	1639	1614	1611	1566	1522	1571
N25	130	9	1582	1555	1562	1483	1479	1573
N11	154	9	1629	1598	1614	1524	1504	1566
N26	154	9	1625	1598	1609	1528	1494	1544
N27	154	9	1571	1539	1555	1501	1459	1539
1° Cyclone			1454	1425	1425	1353	1328	1337
2° Cyclone			1494	1474	1479	1407	1400	1386
Steam to freeboard at N_{22} lb/h			300	350-420	~ 530	560-600	600	200

Table A.1.3.18 SO_2 concentrations and % reductions

Test No.	3.1	3.2	3.3	3.4	3.5	3.6
Fluidising Velocity, ft/s	8	8	8	8	8	4
Bed Temperature, ^{o}F	1560	1560	1560	1560	1560	1560
Bed Height, ft	2.1	2.1	2.1	2.2	3.8	2.3
Ca/S mol ratio	0	1.8	2.1	2.8	2.8	3.0
SO_2 concentration, p.p.m.	1480	910	740	540	540	420
SO_2 reduction, %	0	38	50	64	64	72

Table A.1.3.19 SO_2 concentrations and % reduction during temperature survey

Time, mins.	Bed Temperature ^{o}F	SO_2 concentrations p.p.m.	SO_2 reduction %
0	1571	420	68
10	1580	500	62
18	1614	640	51
20	1598	560	57
25	1625	700	46
35	1492	360	72
40	1544	460	64
45	1499	380	71
50	1544	500	62
60	1468	380	71
68	1578	580	55
72	1517	500	62
80	1634	820	37
88	1526	400	69
92	1632	640	51
120	1562	500	61

The datum SO_2 concentration for the infra-red analyser was taken as 1300 p.p.m.

Table A.1.4.1 Operating conditions during Test Series 4

Coal Coal size Acceptor Acceptor size						Pittsburg coal - 1680 μm Dolomite 1337 - 1680 μm		
Test No.		Datum	4.1	4.2	4.3	4.4	4.5	4.6
Time from start of Test Series (hrs)	Start	0	16	27	38	47	61	82
	End	7	20	31	42	51	65	86
Ca/S mol ratio		0	3.1	2.6	2.7	2.7	2.2	1.6
Coal Rate lb/h dry		123	123	133	119	121	73	60
Fluidising Velocity ft/s		4.0	4.0	4.1	3.8	4.0	2.1	2.2
Bed Temperature °F		1470	1470	1380	1560	1470	1470	1470
Bed Height ft		2.1	2.1	2.1	2.1	2.1	3.7	3.8
Recycle		No	No	No	No	No	No	Yes

Table A.1.4.2 Chemical analyses of coal

Test Number		4.1	4.6
Proximate analysis			
Total moisture	% a.r.	1.6	1.5
Ash	% a.r.	14.8	13.5
Volatile matter	% d.a.f.	-	-
Ultimate analysis			
Carbon	% d.b.	70.5	71.6
Hydrogen	% d.b.	4.3	4.5
Nitrogen	% d.b.	1.4	1.45
Sulphur	% d.b.	2.65	2.7
Oxygen + errors	% d.b.	4.3	4.4
Chlorine	% d.b.	0.1	0.08
Carbon Dioxide	% d.b.	0.7	0.65

Additional samples of coal analysed for sulphur only

Test No.	4.1	4.2	4.3	4.4	4.5	4.6
Sulphur % d.b.	2.65	2.6	2.7	2.6	2.75	2.7

Table A.1.4.3 Size distribution of coal

Test No.	% in grade by weight					
	4.1	4.2	4.3	4.4	4.5	4.6
Particle Size (μm)						
+ 3175	0.1	0	0	0	0.1	0
+ 1680 - 3175	1.0	0.3	0.6	0.5	0.4	0.4
+ 1003 - 1680	13.7	14.0	19.1	20.2	16.2	20.5
+ 500 - 1003	33.0	31.8	32.2	33.7	32.3	32.6
+ 250 - 500	22.7	22.5	20.5	20.2	21.6	20.1
+ 125 - 250	12.2	12.7	11.2	10.8	11.6	11.1
+ 66 - 125	8.0	8.4	7.4	6.8	8.2	7.3
+ 45 - 66	3.2	5.7	2.6	4.6	4.4	4.3
- 45	6.1	4.6	6.4	3.1	5.3	3.6
Median diam. (μm)	474	453	525	560	486	549
Packed bulk density lb/ft^3	58.9	56.9	57.3	57.4	56.0	57.7

Table A.1.4.4. Chemical and size analyses of acceptor

Test No.	4.1	4.4	4.6
Chemical Analysis			
CaO a.r.	29.7	29.8	29.8
MgO a.r.	21.8	22.1	22.1
CO_2 a.r.	47.0	47.1	47.5
SO_2 a.r.	-	-	-
Size Analysis	% in grade by weight		
Particle size (μm)			
+ 3175	0	0	0
+ 1680 - 3175	0.4	0.9	1.4
+ 1003 - 1680	4.5	7.1	7.4
+ 500 - 1003	6.9	12.6	12.2
+ 250 - 500	10.2	9.3	9.9
+ 125 - 250	19.3	19.0	20.3
+ 66 - 125	31.7	27.6	27.7
+ 45 - 66	11.2	10.3	9.6
- 45	15.8	13.2	11.5
Median diam. (μm)	106	122	128
Packed bulk density lb/ft^3	108	112.4	105.5

Table A.1.4.5 Chemical and size analyses of primary cyclone fines

Test No.	4.1	4.2	4.3	4.4	4.5	4.6*
Chemical Analysis						
Carbon % a.r.	12.6	12.9	14.1	15.0	13.0	1.9
Sulphur "	3	2.1	3.2	3.4	3.05	6.95
CO_2 "	11.34	20.9	12.1	9.2	12.3	2.9
CaO "	31.6	27.0	29.2	27.9	25.8	25.6
MgO "	21.5	18.7	19.8	19.7	18.5	18.7
Size Analysis	% in grade by weight					
Particle size (μm)						
+ 3175	0	0	0	0	0	0
+ 1680 - 3175	0	0	0	0	0	0
+ 1003 - 1680	0	0	0	0.2	0.1	0
+ 500 - 1003	0.1	0	0	0.3	0.2	0.1
+ 250 - 500	2.8	4.2	2.8	3.9	1.8	0.1
+ 125 - 250	12.1	18.5	10.6	15.2	14.1	7.8
+ 66 - 125	37.4	35.7	32.4	35.4	37.7	41.1
+ 45 - 66	15.9	13.5	16.8	14.8	15.9	17.4
- 45	31.7	28.1	37.4	30.2	30.2	33.5
Median diam. (μm)	69	79	60	73	71	65
Packed bulk density lb/ft^3	56.7	58.4	58.3	53.3	56.4	80.3

* Note that this analysis refers to a sample of the recycling fines

A.1.4.6 Chemical analyses of secondary cyclone fines

Test No.		4.1	4.2	4.3	4.4	4.5	4.6
Analysis							
Carbon	% a.r.	7.0	9.5	9.3	8.8	13.0	6.2
Sulphur	% a.r.	4.3	4.4	4.1	4.35	3.8	4.05
CO_2	% a.r.	5.34	4.7	4.5	3.42	3.9	3.76
CaO	% a.r.	16.5	14.4	15.4	13.5	12.6	15.1
MgO	% a.r.	10.1	8.7	9.7	8.2	8.0	9.5

Table A.1.4.7 Chemical analyses of exhaust dust

Test No.		4.1	4.2	4.3	4.4	4.5	4.6
Analysis							
Carbon	% a.r.	3.8	4.9	3.8	3.8	9.0	7.4
Sulphur	% a.r.	4.7	4.7	5.35	3.65	3.35	3.1
CO_2	% a.r.	0.14	0.94	0.14	0.14	0.14	0.14
CaO	% a.r.	7.7	9.4	9.8	9.7	8.5	11.0
MgO	% a.r.	3.8	5.0	4.8	5.3	4.7	5.0

Table A.1.4.8a Chemical and size analyses of bed material

Test No.	4.1		4.2			4.3			4.4	
Sample	Initial	Final	Initial	Final	Offtake	Initial	Final	Offtake	Initial	Final
Chemical Analysis										
Sulphur % a.r.	2.1	3.0	3.85	4.3	3.55	5.3	5.1	5.6	5.55	5.6
CO_2 "	1.57	0.26	3.46	3.82	2.49	0.21	0.25	0.36	0.24	0.26
CaO "	11.1	12.3	12.7	14.1	10.9	14.7	14.1	15.4	14.6	14.6
MgO "	3.3	5.2	7.3	8.5	6.3	8.3	8.0	8.8	8.6	8.3
Size Analysis	% in grade by weight									
Particle size (μm)										
+ 3175	0	0	0	0	0	0	0	0	0	0
+ 1680 - 3175	1.9	2.0	2.5	2.1	1.6	1.9	1.8	1.9	1.9	1.7
+ 1003 - 1680	15.1	19.0	22.0	21.8	17.2	21.5	21.2	18.0	23.5	21.5
+ 500 - 1003	40.7	52.1	49.9	44.7	51.4	50.7	50.1	48.2	50.5	51.6
+ 250 - 500	26.1	26.5	25.0	29.3	29.4	25.6	26.7	31.2	23.9	25.0
+ 125 - 250	12.7	0.3	0.4	1.4	0.4	0.2	0.2	0.4	0.2	0.2
+ 66 - 125	2.6	0.1	0.2	0.5	0	0.1	0	0.1	0	0
+ 45 - 66	0.4	0	0	0.1	0	0	0	0	0	0
- 45	0.5	0	0	0.1	0	0	0	0.1	0	0
Median diam (μm)	582	721	745	684	686	738	726	666	723	744
Packed bulk density lb/ft^3	83.1	84.0	84.1	85.2	87.9	86.7	85.6	84.3	88	81.2

A.1.4.8b Chemical and size analyses of bed material

Test No.		4.5			4.6		
Sample		Initial	Final	Offtake	Initial	Final	Offtake
Chemical Analysis							
Sulphur	% a.r.	4.15	4.5	4.65	4.7	4.65	5.4
CO_2	% a.r.	0.2	0.25	0.2	0.25	0.22	0.2
CaO	% a.r.	10.6	11.5	11.6	12.3	12.6	14.0
MgO	% a.r.	6.3	7.0	6.8	7.2	7.3	8.2
Size Analysis		% in grade by weight					
Particle size (µm)							
+ 3175		0.2	0	0	0	0	0
+ 1680	- 3175	1.1	1.6	1.2	1.1	0.9	1.3
+ 1003	- 1680	16.4	17.9	15.4	16.2	14.3	15.6
+ 500	- 1003	47.0	46.0	48.6	42.9	41.1	39.0
+ 250	- 500	30.0	29.1	30.0	28.3	29.7	28.5
+ 125	- 250	5.1	5.3	4.7	9.8	11.3	12.1
+ 66	- 125	0.1	0.1	0.1	1.4	2.3	3.3
+ 45	- 66	0	0	0	0.2	0.2	0.1
- 45		0.1	0	0	0.1	0.2	0.1
Median diam. (µm)		638	650	641	602	561	560
Packed bulk density lb/ft^3		86.2	86.3	84.5	84.4	87.8	91.3

Table A.1.4.9a Flue gas analyses

Test No.		Datum	4.1				4.2			4.3		
Time from start (h)			1	2	4	Mean	1	2	Mean	1	3	Mea
Operating Conditions												
Ca/S mol ratio		0				3.0			2.6			2.
Fluidising Velocity ft/s		4.0				4.0			4.0			3.8
Bed Temperature ^oF		1470				1470			1380			156
Bed Height ft		2.1				2.1			2.1			2.
Recycle		No				No			No			N
Gas Analysis	**Method**											
Vol % dry gas CO_2	Chromatograph	15.3	16.9	16.0	16.7	16.5	15.2	15.7	15.7	15.9	15.6	15.
" O_2	"	2.5	2.6	3.3	3.1	3.0	3.9	3.7	3.7	2.6	3.1	2.9
" CO	"	0	0	0	0	0	0	0	0	0	0	0
" CH_4	"	0	0	0	0	0	0	0	0	0	0	0
p.p.m. NO_x	Saltzman's					234					(245 (244	24
" SO_2	Iodine	2240				380			620			60
" SO_2	I.R.A.	2000				290			510			41
" SO_2	H_2O_2					350			570			630
" Cl	"					46			44			5
" NH_3	"					34			6			6

Table A.1.4.9b Flue gas analyses

Test No.		4.4			4.5				4.6			
Time from start (h)		0	1	Mean	1.5	2.5	3	Mean	-2	0	3.5	Mean
Operating Conditions												
Ca/s mol ratio				2.7				2.2				1.6
Fluidising Velocity ft/s				4.0				2.1				2.2
Bed Temperature °F				1470				1470				1470
Bed Height ft				2.1				3.7				3.8
Recycle				No				No				Yes
Gas Analysis	**Method**											
Vol % dry gas CO_2	Chromatograph	15.3	15.0	15.2	16.7	16.7		16.7		15.7	16.7	16.3
" O_2	"	3.8	3.8	3.8	2.8	2.7		2.8		3.2	3.1	3.1
" CO	"	0	0	0	0	0		0		0	0	0
" CH_4	"	0	0	0	0	0		0		0	0	0
p.p.m. NO_x	Saltzman's			-			360	360	398 386			392
" SO_2	Iodine			580				380				20
" SO_2	I.R.A.			460				380				20
" SO_2	H_2O_2			570				380				22
" Cl	"			42				29				38
" NH_3	"			6				7				8

Table A.1.4.10 Mass balance for Test 4.1

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium	Magnesium
Coal Feed	123.0	17.8	87.3	0	5.3	3.32	1.08	0
Acceptor Feed	61.0	46.2	0	0	0	0	12.93	8.1
Total Air	1285.9	0	0	988	297.9	0	0	0
Total Input	1469.9	64.0	87.3	988	303.2	3.32	14.01	8.1
Accumulated in bed	0	0	0	0	0	1.04	1.04	1.30
Offtake Ash	7.0	7.0	0	0	0	0.18	0.58	0.18
Primary Fines	63.0	55.1	7.94	0	0	1.89	14.17	8.13
Secondary Fines	2.0	1.9	0.14	0	0	0.09	0.24	0.12
Exhaust Dust	0.5	0.5	0.02	0	0	0.02	0.03	0.01
Flue Gas	1397.7	0	80.8	990	303.4	0.49	0	0
Total Output	1470.2	64.5	88.9	990	303.4	3.71	16.06	9.74
Loss (In - Out)	- 0.3	-0.5	-1.6	- 2	- 0.2	-0.39	-2.05	-1.64
Loss Percent	0	-0.8	-1.7	-0.2	- 0.1	-11.7	-14.5	-20.3

Excess air	7.1%
Carbon loss	9.1% (Unburnt)
Sulphur retention	85%
Ca/S mol ratio	3.1

Table A.1.4.11 Mass balance for Test 4.2

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium	Magnesium
Coal Feed	132.8	19.3	94.3	0	5.7	3.45	1.17	0
Acceptor Feed	53.6	40.7	0	0	0	0	11.36	7.13
Total Air	1384.9	0	0	1064	320.9	0	0	0
Total Input	1571.3	60.0	94.3	1064	326.6	3.45	12.53	7.13
Accumulated in bed	0	0	0	0	0	0.52	1.16	0.81
Offtake Ash	14.0	14.0	0	0	0	0.57	1.34	0.66
Primary Fines	55.0	47.9	7.09	0	0	1.15	10.61	6.15
Secondary Fines	2.0	1.8	0.19	0	0	0.09	0.21	0.10
Exhaust Dust	0.6	0.6	0.03	0	0	0.03	0.04	0.02
Flue Gas	1500.5	0	84.2	1064	329.9	0.87	0	0
Total Output	1572.1	64.3	91.5	1064	329.9	3.23	13.36	7.74
Loss (In - Out)	-0.8	-4.3	2.8	0	-3.3	0.22	-0.83	-0.61
Loss Percent	-0.1	-7.2	3.0	0	-1.0	6.4	-6.6	-8.6

Excess air	12.3%	
Carbon loss	8.0%	(Unburnt)
Sulphur retention	75%	
Ca/S mol ratio	2.6	

Table A.1.4.12 Mass balance for Test 4.3

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium	Magnesium
Coal Feed	119.1	17.3	84.5	0	5.1	3.21	1.05	0
Acceptor Feed	52.0	39.6	0	0	0	0	11.02	6.90
Total Air	1181.9	0	0	908	273.9	0	0	0
Total Input	1353.0	56.9	84.5	908	279.0	3.21	12.07	6.90
Accumulated in bed	0	0	0	0	0	-0.24	-0.48	-0.24
Offtake Ash	8.0	8.0	0	0	0	0.42	0.82	0.40
Primary Fines	57.0	49.0	8.04	0	0	1.82	11.91	6.77
Secondary Fines	2.8	2.5	0.26	0	0	0.11	0.31	0.16
Exhaust Dust	0.7	0.6	0.03	0	0	0.04	0.05	0.02
Flue Gas	1280.3	0	70.8	918	270.8	0.77	0	0
Total Output	1348.8	60.1	79.1	918	270.8	2.92	12.61	7.11
Loss (In - Out)	4.2	-3.2	5.4	-10	8.2	0.29	-0.54	-0.21
Loss Percent	0.3	-5.6	6.4	-1.1	2.9	9.2	-4.4	-3.0

Excess air	5.8%
Carbon loss	10.5% (Unburnt)
Sulphur retention	76%
Ca/S mol ratio	2.7

Table A.1.4.13 Mass balance for Test 4.4

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium	Magnesium
Coal Feed	121.0	17.5	85.9	0	5.2	3.15	1.07	0
Acceptor Feed	49.0	37.3	0	0	0	0	10.44	6.51
Total Air	1285.9	0	0	988	297.9	0	0	0
Total Input	1455.9	54.8	85.9	988	303.1	3.15	11.51	6.51
Accumulated in bed	0	0	0	0	0	0.06	0	-0.23
Offtake Ash	6.0	6.0	0	0	0	0.33	0.62	0.32
Primary Fines	48.0	40.8	7.20	0	0	1.63	9.55	5.66
Secondary Fines	1.8	1.6	0.16	0	0	0.08	0.17	0.09
Exhaust Dust	0.5	0.5	0.02	0	0	0.02	0.04	0.02
Flue Gas	1388.2	0	74.6	996	297.2	0.78	0	0
Total Output	1444.5	48.9	82.0	996	297.2	2.90	10.38	5.86
Loss (In - Out)	11.4	5.9	3.9	-8	5.9	0.25	1.13	0.65
Loss Percent	0.7	10.8	4.6	-0.8	1.9	7.8	9.8	10.0

Excess air	12.7%
Carbon loss	9.0% (Unburnt)
Sulphur retention	75%
Ca/S mol ratio	2.7

Table A.1.4.14 Mass balance for Test 4.5

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium	Magnesium
Coal Feed	72.8	10.6	51.7	0	3.1	2.00	0.64	0
Acceptor Feed	26.0	19.8	0	0	0	0	5.54	3.46
Total Air	700.2	0	0	538	162.2	0	0	0
Total Input	799.0	30.4	51.7	538	165.3	2.00	6.18	3.46
Accumulated in bed	0	0	0	0	0	0.81	1.39	0.93
Offtake Ash	3.0	3.0	0	0	0	0.13	0.24	0.12
Primary Fines	28.0	24.3	3.67	0	0	0.85	5.15	3.10
Secondary Fines	1.2	1.0	0.16	0	0	0.05	0.11	0.06
Exhaust Dust	1.0	0.9	0.09	0	0	0.03	0.06	0.03
Flue Gas	762.0	0	45.0	537	168.6	0.28	0	0
Total Output	795.2	29.2	48.9	537	168.6	2.15	6.95	4.24
Loss (In - Out)	4.8	1.2	2.8	1	-3.3	-0.15	-0.77	0.78
Loss Percent	0.6	3.9	5.4	0.2	-2.0	-7.5	-12.4	-22.5

Excess air	6.8%
Carbon loss	8.0% (Unburnt)
Sulphur retention	86%
Ca/S mol ratio	2.2

Table A.1.4.15 Mass balance for Test 4.6

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium	Magnesium
Coal Feed	60.0	8.7	42.6	0	2.6	1.62	0.53	0
Acceptor Feed	15.2	11.6	0	0	0	0	3.24	2.02
Total Air	726.4	0	0	558	168.4	0	0	0
Total Input	801.6	20.3	42.6	558	171.0	1.62	3.77	2.02
Accumulated in bed	6.5	6.5	0	0	0	0.18	0.89	0.45
Offtake Ash	2.5	2.5	0	0	0	0.11	0.22	0.11
Primary Fines	0	0	0	0	0	0	0	0
Secondary Fines	3.0	2.8	0.19	0	0	0.12	0.32	0.18
Exhaust Dust	1.6	1.5	0.12	0	0	0.05	0.13	0.05
Flue Gas	783.8	0	45.8	561	169.3	0.02	0	0
Total Output	797.4	13.3	46.1	561	169.3	0.48	1.56	0.79
Loss (In - Out)	4.2	7.0	-3.5	- 3	1.7	1.14	2.21	1.23
Loss Percent	0.5	34.5*	-8.3	-0.5	1.0	70.3*	58.6*	60.9*

Excess air	16.4%
Carbon loss	0.7% (Unburnt)
Sulphur retention	99%
Ca/S mol ratio	1.6
Fines recycle rate	320 lb/h

* These poor balances are probably the result of the weight of fines in the recycle system increasing during the balance.

Table A.1.4.16 Pressure drops through the combustor

Test No.	4.1	4.2	4.3	4.4	4.5	4.6
Fluidising Velocity ft/s	4.0	4.1	3.8	4.0	2.1	2.2
Bed Height ft	2.1	2.1	2.1	2.1	3.7	3.8
	Pressure drop, inches w.g.					
Baseplate	11	12.5	9	10.5	4.5	5.5
Bed	20	20	21	20	41	39
Density (over 8 in)	6.3	6.3	6.7	6.3	7.2	6.8
1^{o} Cyclone	1	1	1	1	0.5	0.5
2^{o} Cyclone	3	3	3	3	1	1

Table A.1.4.17 Temperature distribution through the combustor

APCO Test No.			4.1	4.2	4.3	4.4	4.5	4.6
Fluidising Velocity ft/s			4.0	4.1	3.8	4.0	2.1	2.2
Bed Height ft			2.1	2.1	2.1	2.1	3.7	3.8
Excess air			6.8	11.9	5.6	12.1	6.6	15.8
Probe Number	Height above bubble caps (ins)	Projection into combustor (ins)	Temperature °F					
N2	4	3	1477	1384	1566	1474	1486	1477
N14	4	9	1481	1387	1566	1477	1476	1470
N3	12	3	1486	1389	1571	1483	1483	1477
N4	12	9	1479	1393	1567	1479	1468	1459
N15	12	3	1476	1382	1562	1474	1474	1468
N5	20	9	1485	1387	1564	1474	1468	1456
N20	50	9	1530	1458	1600	1530	1497	1490
N9	94	9	1591	1530	1485	1591	1508	1517
N23	94	9	1589	1528	1560	1594	1510	1517
N10	130	9	1576	1524	1494	1585	1472	1512
N25	130	9	1584	1531	1470	1594	1483	1522
N11	154	9	1576	1530	1477	1587	1456	1515
N26	154	9	1564	1519	1468	1576	1445	1504
N27	154	9	1551	1506	1440	1567	1432	1490
1° Cyclone			1355	1317	1270	1353	1216	1247
2° Cyclone			1404	1387	1328	1411	1225	1321
Steam to freeboard at N22. lb/h			0	0	200	0	0	0

Table A.1.4.18 SO_2 concentrations and % reductions

Test No.	Datum	4.1	4.2	4.3	4.4	4.5	4.6
Fluidising Velocity, ft/s	4.0	4.0	4.1	3.8	4.0	2.1	2.2
Bed Temperature, °F	1470	1470	1380	1560	1470	1470	1470
Bed Height, ft	2.1	2.1	2.1	2.1	2.1	3.7	5.8
Fines Recycle	No	No	No	No	No	No	Yes
Ca/S mol ratio	0	3.1	2.6	2.7	2.7	2.2	1.6
SO_2 concentration, p.p.m.	2240	380	620	600	580	380	20
SO_2 reduction, %	0	83	72	73	74	83	99

Table A.1.5.1 Operating Conditions during Test Series 5

Coal	Pittsburg coal
Coal size	-3175 μm
Acceptor	Limestone 18
Acceptor size	-3175 μm
Bed Temperature	1560°F
Recycle	System not in operation

Test No.		Datum	5.1	5.2	5.3	5.4	5.5
Time from start of Test Series (hrs)	Start	6	24	37	51	65	85
	End	14	28	41	55	69	105
Ca/S mol ratio		0	1.7	1.6	1.9	5.7	6
Coal Rate lb/h dry		122	122	247	253	253	245
Fluidising Velocity ft/s		4.0	4.0	8.0	7.8	8.0	8.0
Bed Height ft.		2.1	2.1	2.2	3.5	3.6	3.6

Table A.1.5.2 Chemical analyses of coal

Test Number		5.4
Proximate analysis		
Total moisture	% a.r.	1.5
Ash	% a.r.	15.5
Volatile matter	% d.a.f.	-
Ultimate analysis		
Carbon	% d.b.	69.5
Hydrogen	% d.b.	4.3
Nitrogen	% d.b.	1.4
Sulphur	% d.b.	2.8
Oxygen + errors	% d.b.	4.5
Chlorine	% d.b.	0.1
Carbon Dioxide	% d.b.	0.7

Additional samples of coal analysed for sulphur only

Test No.	5.1	5.2	5.3	5.4
Sulphur % d.b.	2.85	2.8	2.75	2.8

Table A.1.5.3 Size distribution of coal

Test No.	% in grade by weight			
	5.1	5.2	5.3	5.4
Particle Size (μm)				
+ 3175	0.3	0.4	0.6	0.4
+ 1680 - 3175	17.7	24.7	25.8	19.3
+ 1003 - 1680	17.1	17.7	19.7	18.1
+ 500 - 1003	22.6	19.8	19.5	21.7
+ 250 - 500	15.0	14.8	11.6	16.9
+ 125 - 250	9.5	8.8	7.4	11.0
+ 66 - 125	7.7	6.0	6.0	6.6
+ 45 - 66	3.5	2.6	3.2	3.7
- 45	6.6	5.2	6.2	2.3
Median diam. (μm)	648	803	893	677
Packed bulk density lb/ft^3	60.1	57.4	58.0	59.6

Table A.1.5.4 Chemical and size analyses of acceptor

Test No.		5.1	5.2	5.4
Chemical Analysis				
CaO	a.r..	44.5	-	43.7
MgO	a.r.	-	-	-
CO_2	a.r.	36.8	-	36.2
S_1O_2	a.r.	-	-	-
Size Analysis		% in grade by weight		
Particle size (μm)				
+ 3175		0	0	0
+ 1680	- 3175	9	8.9	17.6
+ 1003	- 1680	12.4	12.0	15.1
+ 500	- 1003	17.0	16.0	17.0
+ 250	- 500	23.2	23.5	18.1
+ 125	- 250	16.7	17.1	12.4
+ 66	- 125	8.9	10.1	8.4
+ 45	- 66	3.5	3.9	2.1
- 45		9.3	8.5	9.3
Median diam. (μm)		362	343	495
Packed bulk density lb/ft^3		122.4	-	114.4

Table A.1.5.5 Chemical and size analyses of primary cyclone fines

Test No.	5.1	5.2	5.3	5.4
Chemical Analysis				
Carbon % a.r.	20.8	25.1	25.1	19.4
Sulphur "	3.3	2.9	2.9	2.5
CO_2 "	3.5	3.4	4.64	4.37
CaO "	25.6	24.5	25.2	36.2
Size Analysis	% in grade by weight			
Particle (μm)				
+ 3175	0	0	0	0
+ 1680 - 3175	0	0	0.1	0.1
+ 1003 - 1680	0	0.1	0.1	0.1
+ 500 - 1003	0.1	2.5	4.6	2.8
+ 250 - 500	8.4	14.5	13.2	9.9
+ 125 - 250	32.5	19.1	18.9	15.7
+ 66 - 125	24.5	21.7	23.5	20.7
+ 45 - 66	7.5	8.1	7.7	9.8
- 45	27.0	34.0	31.9	40.9
Median diam. (μm)	102	87	93	64
Packed bulk density lb/ft^3	51.2	58.9	48.5	48.9

Table A.1.5.6 Chemical analyses of secondary cyclone fines

Test No.		5.1	5.2	5.3	5.4
Analysis					
Carbon	% a.r.	7.7	4.5	8.7	2.5
Sulphur	% a.r.	4.6	5.4	5.6	6.45
CO_2	% a.r.	3.8	2.6	3.5	9.1
CaO	% a.r.	19.6	21.0	24.1	44.4

Table A.1.5.7 Chemical analyses of exhaust dust

Test No.		5.1	5.2	5.3	5.4
Analysis					
Carbon	% a.r.	4.5	5.4	5.7	1.7
Sulphur	% a.r.	5.0	5.1	6.4	9.1
CO_2	% a.r.	1.0	1.0	1.0	4.7
CaO	% a.r.	12.5	17.5	18.9	36.8

Table A.1.5.8a Chemical and size analyses of bed material

Test No.	5.1			5.2			5.3		5.4		
Sample	Initial	Final	Offtake	Initial	Final	Offtake	Initial	Final	Initial	Final	Offtake
Chemical Analysis											
Sulphur % a.r.	1.55	2.7	1.5	3.85	3.3	3.4	3.55	3.65	3.8	3.8	3.2
CO_2 "	0.33	0.21	0.18	0.2	0.24	0.17	0.26	0.23	1.65	0.85	0.29
CaO "	9.1	14.1	9.1	19.5	15.6	16.5	15.7	15.7	21.7	21.2	17.8
Size Analysis	% in grade by weight										
Particle size (μm)											
+ 3175	0.8	0.5	0.6	0.6	0.5	0.8	1.0	1.0	0.2	0.5	1.5
+ 1680 - 3175	18.3	27.7	29.3	20.7	25.1	35.5	29.8	31.0	27.3	26.9	41.2
+ 1003 - 1680	14.8	21.1	24.3	27.3	30.0	)	32.8	)	30.2	31.9	28.8
+ 500 - 1003	23.3	27.0	30.7	45.1	40.0	)27.9	34.8	)30.7	40.4	38.8	26.3
+ 250 - 500	31.0	22.7	14.9	6.0	4.2	32.0	1.5	35.5	1.8	1.7	1.8
+ 125 - 250	10.0	0.8	0.2	0.2	0.1	3.7	0.1	1.6	0.1	0.2	0.3
+ 66 - 125	1.2	0.2	0	0.1	0.1	0.1	0	0.1	0	0	0.1
+ 45 - 66	0.3	0	0	0	0	0	0	0	0	0	0
- 45	0.3	0	0	0	0	0	0	0.1	0	0	0
Median diam. (μm)	580	987	1090	983	1094	780	1245	750	1129	1157	1491
Packed bulk density lb/ft^3	88.1	81.4	87.9	86.4	81.7	92.2	87.7	86.5	84.2	82.0	82.9

Table A.1.5.8b Chemical and size analyses of bed material

Test No.	5.5				
Time from start (h)	2	5	8	11.5	16.5
Chemical Analysis					
Sulphur % a.r.	3.75	3.9	3.55	4.25	3.75
CO_2 % a.r.	0.38	0.49	0.52	0.55	0.6
CaO % a.r.	20.6	22.7	24.6	26.5	26.4
Size Analysis	% in grade by weight				
Particle size (μm)					
+ 3175	0.4	0.3	0.3	0.5	0.2
+ 1680 - 3175	28.2	28.8	23.4	24.3	21.3
+ 1003 - 1680	29.9	27.7	29.9	29.8	27.4
+ 500 - 1003	37.5	39.3	42.8	41.7	47.2
+ 250 - 500	3.7	3.5	3.5	3.3	3.8
+ 125 - 250	0.2	0.2	0.1	0.2	0.1
+ 66 - 125	0.1	0.1	0	0.2	0
+ 45 - 66	0	0	0	0	0
- 45	0	0	0	0	0
Median diam. (μm)	1150	1119	1058	1075	986
Packed bulk density lb/ft^3	82.7	87.0	83.1	83.5	83.1

Table A.1.5.9a Flue gas analyses

Test No.		Datum	5.1			5.2			5.3		
Time from start (h)			0	3	Mean	2	3.75	Mean	0	2	Mean
Operating Conditions											
Ca/S mol ratio		0			1.7			1.6			1.9
Fluidising Velocity ft/s		4.0			4.0			8.0			7.8
Bed Temperature ^{o}F		1560			1560			1560			1560
Bed Height ft		2.1			2.1			2.2			3.5
Gas Analysis	**Method**										
Vol % dry gas CO_2	Chromatograph		15.2	15.2	15.2	15.7	14.6	15.3	16.2	16.2	16.2
" O_2	"		3.1	3.2	3.2	2.8	3.8	3.2	2.3	2.4	2.4
" CO	"		0	0	0	0	0	0	0	0	0
" CH_4	"		0	0	0	0	0	0	0	0	0
p.p.m. NO_x	Saltzman's	280 330				450 440		445			-
" SO_2	Iodine	1850			850			1180			1040
" SO_2	I.R.A.	2060			650			950			1000
" SO_2	H_2O_2	-			780			1180			1050
" Cl	"	-			60			65			65
" NH_3	"	-			2			4			2

Table A.1.5.9b Flue gas analyses

Test No.		5.4			5.5			
Time from start (h)		1	2.5	Mean	3	9	16	Mean
Operating Conditions								
Ca/S mol ratio				5.7				6
Fluidising Velocity ft/s				8.0				8.0
Bed Temperature ^{o}F				1560				1560
Bed Height ft.				3.6				3.6
Gas Analysis	**Method**							
Vol % dry gas CO_2	Chromatograph	18.0	17.2	16.2	16.8	17.0	16.9	16.9
" O_2	"	2.4	2.2	2.8	3.3	3.0	2.9	3.0
" CO	"	0	0	0	0	0	0	0
" CH_4	"	0	0	0	0	0	0	0
p.p.m. NO_X	Saltzman's	560		560	550		307 341	-
" SO_2	Iodine			80				11
" SO_2	I.R.A.			0				0
" SO_2	H_2O_2			54				-
" Cl	"			30				-
" NH_3	"			3				-

Table A.1.5.10 Mass balance for Test 5.1

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium
Coal Feed	122.1	19.2	84.9	0	5.5	3.42	1.07
Acceptor Feed	23.0	23.0	0	0	0	0	7.31
Total Air	1262.6	0	0	970	292.6	0	0
Total Input	1407.7	42.2	84.9	970	298.1	3.42	8.38
Accumulated in bed	0	0	0	0	0	1.25	3.92
Offtake Ash	16.0	16.0	0	0	0	0.34	1.33
Primary Fines	33.0	26.1	6.86	0	0	1.09	6.04
Secondary Fines	2.1	1.9	0.16	0	0	0.10	0.29
Exhaust Dust	0.8	0.8	0.04	0	0	0.04	0.07
Flue Gas	1356.9	0	77.3	976	295.1	1.13	0
Total Output	1408.8	44.8	84.3	976	295.1	3.95	11.65
Loss (In - Out)	-1.1	-2.6	0.6	-6	3.0	-0.53	-3.27
Loss Percent	-0.08	-6.2	0.7	-0.6	1.0	-15.5	-38.9

Excess air	9.3%
Carbon loss	8.4% (Unburnt)
Sulphur retention	67%
Ca/S mol ratio	1.7

Table A.1.5.11 Mass balance for Test 5.2

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium
Coal Feed	247.2	38.8	171.8	0	11.1	6.92	2.18
Acceptor Feed	43.5	43.5	0	0	0	0	13.83
Total Air	2494.0	0	0	1916	578.0	0	0
Total Input	2784.7	82.3	171.8	1916	589.1	6.92	16.01
Accumulated in bed	0	0	0	0	0	-0.44	-2.24
Offtake Ash	12.0	12.0	0	0	0	0.43	1.50
Primary Fines	78.1	58.5	19.60	0	0	2.26	13.67
Secondary Fines	1.9	1.8	0.09	0	0	0.10	0.29
Exhaust Dust	1.7	1.7	0.09	0	0	0.09	0.22
Flue Gas	2682.6	0	153.7	1924	587.5	3.10	0
Total Output	2776.3	74.0	173.5	1924	587.5	5.54	13.44
Loss (In - Out)	8.4	8.3	-1.7	-8	1.6	1.38	2.57
Loss Percent	0.3	10.1	-1.0	-0.4	0.3	19.9	16.1

Excess air	6.1%
Carbon loss	11.4% (Unburnt)
Sulphur retention	55%
Ca/S mol ratio	1.6

Table A.1.5.12 Mass balance for Test 5.3

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen	Sulphur	Calcium
Coal Feed	253.1	39.7	175.9	0	11.4	7.09	2.23
Acceptor Feed	54.0	54.0	0	0	0	0	16.85
Total Air	2432.8	0	0	1869	363.8	0	0
Total Input	2739.9	93.7	175.9	1869	575.2	7.09	19.08
Accumulated in bed	0	0	0	0	0	0.15	0
Offtake Ash	6.0	6.0	0	0	0	0.22	0.67
Primary Fines	108.0	80.9	27.11	0	0	3.13	19.44
Secondary Fines	4.1	3.7	0.36	0	0	0.23	0.71
Exhaust Dust	2.1	2.0	0.12	0	0	0.14	0.28
Flue Gas	2627.8	0	158.5	1872	579.5	2.66	0
Total Output	2748.0	92.6	186.1	1872	579.5	6.53	21.10
Loss (In - Out)	-8.1	1.1	-10.2	-3	-4.3	0.56	-2.02
Loss Percent	-0.3	1.2	-5.8	-0.1	-0.7	7.9	-10.6

Excess air	-1.9%
Carbon loss	14.8% (Unburnt)
Sulphur retention	62%
Ca/S mol ratio	1.9

Table A.1.5.13 Mass balance for Test 5.4

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium
Coal Feed	253.1	39.7	175.9	0	11.4	7.09	2.23
Acceptor Feed	163.0	113.8	0	0	0	0	50.86
Total Air	2494.0	0	0	1916	578.0	0	0
Total Input	2910.1	153.5	175.9	1916	589.4	7.09	53.09
Accumulated in bed	0	0	0	0	0	0	-0.47
Offtake Ash	16.5	16.5	0	0	0	0.63	2.52
Primary Fines	190.0	153.1	36.86	0	0	4.75	49.02
Secondary Fines	6.0	5.8	0.15	0	0	0.39	1.90
Exhaust Dust	4.5	4.5	0.08	0	0	0.41	1.19
Flue Gas	2744.8	0	162.6	1911	602.8	0.21	0
Total Output	2961.8	179.9	199.7	1911	602.8	6.38	54.17
Loss (In - Out)	-51.7	-26.4	-23.8	5	-13.4	0.71	-1.08
Loss Percent	-1.8	-17.2	-13.5	0.3	-2.3	10.0	-2.1

Excess air	-3.9%	
Carbon loss	18.6%	(Unburnt)
Sulphur retention	97%	
Ca/S mol ratio	5.7	

Table A.1.5.14 Pressure-drops through the combustor

Test No.	5.1	5.2	5.3	5.4
Fluidising Velocity ft/s	4.0	8.0	7.8	8.0
Bed Height ft.	2.1	2.2	3.5	3.6
	Pressure-drop, inches w.g.			
Baseplate	11	36	33	33
Bed	22	17	29	28
Density (over 8 ins.)	6.8	4.8	5.6	5.2
1^{o} Cyclone	0.5	2.5	2	2
2^{o} Cyclone	3.5	15	14.5	15

Table A.1.5.15 Temperature distribution through the combustor

APCO Test No.			5.1	5.2	5.3	5.4
Fluidising Velocity ft/s			4.0	8.0	7.8	8.0
Bed Height ft.			2.1	2.2	3.5	3.6
Excess Air %			9.3	6.1	-1.9	-3.9
Probe Number	Height above bubble caps (ins)	Projection into combustor (ins)	Temperature ^{o}F			
N 2	4	3	1567	1546	1535	1531
N14	4	9	1573	1584	1564	1562
N 3	12	3	1578	1584	1569	1575
N 4	12	9	1576	1602	1580	1564
N15	12	3	1566	1564	1566	1566
N 5	20	9	1540	1562	1548	1544
N20	50	9	1585	1603	1600	1596
N 9	94	9	1605	1420	1404	1519
N23	94	9	1627	1600	1548	1594
N10	130	9	1548	1576	1504	1546
N25	130	9	1560	1513	1459	1506
N11	154	9	1548	1557	1479	1533
N26	154	9	1530	1549	1470	1526
N27	154	9	1517	1497	1434	1483
1° Cyclone			1335	1375	1308	1353
2° Cyclone			1371	1432	1375	1429
Steam to freeboard at N22 lb/h			150	400	400	300

Table A.1.5.16 SO_2 concentrations and % reductions

Test No.	Datum	5.1	5.2	5.3	5.4	5.5
Fluidising Velocity, ft/s	4	4	8	8	8	8
Bed Temperature °F	1560	1560	1560	1560	1560	1560
Bed Height, ft	2	2	2	3.5	3.6	3.6
Ca/S mol ratio	0	1.7	1.6	1.9	5.7	6
SO_2 concentration, p.p.m.	1850	850	1180	1040	80	11
SO_2 reduction, %	0	65	51	57	97	100

The datum SO_2 concentration for these tests was taken as 2400 p.p.m. This value was calculated by multiplying the datum of Series 2, 2050 p.p.m., by the ratio of the sulphur contents of the coal, 2.8/2.4

Table A.1.5.17 Variation in SO_2 concentration 2 ft above bed

Test No.	SO_2 concentration, p.p.m.			
	Above feed	3 in from feed	6 in from feed	Stack
Datum	2350	1950	1250	2400*
5.1	[illegible]	-	400	850
5.2	2150	-	1400	1180

Values taken from Fig. 5.1

* Value based on infra-red analyser reading.

Table A.1.6.1 Operating Conditions during Test Series 6

Coal	Pittsburg coal
Coal size	-3175 μm
Acceptor	Dolomite 1337
Acceptor size	-3175 + 500 μm
Recycle	System not in operation

Test No.		Datum	6.1	6.2	6.3	Temperature Survey	6.4	6.5
Time from start of Test Series (hrs)	Start	0	6	24	34	40	68	84
	End	1	10	28	38	41	72	88
Ca/S mol ratio		0	2.5	5.4	5.3	5.3	5.2	5.0
Coal Rate lbs/hr dry		247	247	244	253	253	256	253
Bed Height ft.		2.7	2.7	2.7	4.0	4.0	7.3-6.4	5.5
Fluidising Velocity ft/s		8.0	8.0	8.0	8.1	8.2-7.5	8.0	8.0
Bed Temperature ^{o}F		1560	1560	1560	1560	1620-1420	1560	1560

Table A.1.6.2 Chemical analyses of coal

Test Number		6.3
Proximate analysis		
Total moisture	% a.r.	1.7
Ash	% a.r.	14.0
Volatile Matter	% d.a.f.	-
Ultimate analysis		
Carbon	% d.b.	70.8
Hydrogen	% d.b.	4.5
Nitrogen	% d.b.	1.5
Sulphur	% d.b.	2.6
Oxygen + errors	% d.b.	4.4
Chlorine	% d.b.	0.08
Carbon Dioxide	% d.b.	0.95

Additional coal samples analysed for sulphur only

Test No.	6.1	6.2	6.3	6.5
Sulphur % d.b.	2.7	2.6	2.6	2.7

Table A.1.6.3 Size distribution of coal

Test No.	% in grade by weight			
	6.1	6.2	6.3	6.5
Particle Size (μm)				
+ 3175	0.7	0.7	0.4	0.2
+ 1680 - 3175	15.9	20.3	19.3	13.7
+ 1003 - 1680	17.5	18.6	19.5	17.3
+ 500 - 1003	23.1	23.3	20.8	22.7
+ 250 - 500	16.9	16.3	15.5	18.2
+ 125 - 250	9.3	8.9	9.1	10.0
+ 66 - 125	7.1	9.9	7.0	7.9
+ 45 - 66	3.1	1.8	3.6	5.2
- 45	6.4	0.2	4.8	4.8
Median diam. (μm)	627	757	702	564
Packed bulk density lb/ft^3	60.6	62.3	62.5	63.4

Table A.1.6.4 Chemical and size analyses of acceptor

Test No.	6.1	6.5
Chemical Analysis		
CaO a.r.	29.5	29.7
MgO a.r.	21.8	22.0
CO_2 a.r.	47.0	47.0
S_1O_2 a.r.	-	-
Size Analysis	% in grade by weight	
Particle size (μm)		
+ 3175	0	0
+ 1680 - 3175	14.9	20.9
+ 1003 - 1680	28.1	30.0
+ 500 - 1003	30.3	25.2
+ 250 - 500	8.9	9.0
+ 125 - 250	4.2	4.1
+ 66 - 125	5.7	5.3
+ 45 - 66	2.3	2.1
- 45	5.6	3.4
Median diam. (μm)	874	1022
Packed bulk density lb/ft^3	111.1	104.1

Table A.1.6.5 Chemical and Size analyses of primary cyclone fines

Test No.	6.1	6.2	6.3	6.4	6.5
Chemical Analysis					
Carbon % a.r.	19.2	13.3	14.8	13.2	14.5
Sulphur "	3.05	2.95	2.8	2.5	2.65
CO_2 "	5.52	3.88	3.49	2.51	3.76
CaO "	27.3	34.4	36.4	27.7	32.8
MgO "	18.5	24.3	23.2	19.5	22.3
Size Analysis	% in grade by weight				
Particle size (μm)					
+ 3175	0	0	0	0.1	0
+ 1680 - 3175	0	0	0	2.5	0.6
+ 1003 - 1680	0	0	0.2	5.1	1.7
+ 500 - 1003	1.4	1.1	2.0	15.1	4.9
+ 250 - 500	5.3	4.4	4.5	5.0	4.7
+ 125 - 250	9.1	9.3	10.8	8.5	10.0
+ 66 - 125	31.3	34.1	36.2	24.8	29.4
+ 45 - 66	17.4	17.6	18.4	13.8	15.6
- 45	35.5	33.5	27.9	25.1	33.1
Median diam. (μm)	62	65	71	87	68
Packed bulk density lb/ft^3	57.5	49.4	56.3	57.7	51.9

Table A.1.6.6 Chemical analyses of secondary cyclone fines

Test No.		6.1	6.2	6.3	6.4	6.5
Analysis						
Carbon	% a.r.	4.1	2.4	3.7	2.3	3.1
Sulphur	% a.r.	4.9	5.35	5.95	7.7	7.7
CO_2	% a.r.	2.8	4.5	5.45	3.62	5.74
CaO	% a.r.	17.0	23.4	24.9	27.2	28.0
MgO	% a.r.	10.5	14.9	15.4	19.2	18.7

Table A.1.6.7 Chemical analyses of exhaust dust

Test No.		6.1	6.2	6.3	6.4	6.5
Analysis						
Carbon	% a.r.	3.6	1.8	1.7	1.1	1.1*
Sulphur	% a.r.	6.8	8.3	8.9	10.6	10.6*
CO_2	% a.r.	0.75	0.75	0.75	0.75	0.75*
CaO	% a.r.	17.6	19.0	19.0	24.0	24.0*
MgO	% a.r.	8.2	12.3	11.3	15.3	15.3*

* Estimates

Table A.1.6.8 Chemical and size analyses of bed material

Test No.	6.1		6.2		6.3		6.4		6.5	
Sample	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final
Chemical Analysis										
Sulphur % a.r.	1.2	1.9	3.1	3.65	3.15	3.25	1.45	1.5	1.55	1.6
CO_2 % a.r.	0.13	0.21	0.27	0.26	0.27	0.15	0.16	0.18	0.2	0.13
CaO % a.r.	5.7	7.8	11.9	14.3	11.2	11.9	5.2	6.0	6.4	6.9
MgO % a.r.	-	-	-	-	-	-	-	-	-	-
Size Analysis	% in grade by weight									
Particle size (μm)										
+ 3175	0.2	0.3	0.2	0.2	0.4	0.1	0.2	0.7	0.2	0.3
+ 1680 - 3175	27.3	25.4	25.0	23.5	25.3	24.2	25.0	29.2	35.3	33.4
+ 1003 - 1680	36.2	37.9	36.9	39.2	37.6	37.5	42.4	41.7	42.6	43.6
+ 500 - 1003	32.8	33.4	35.0	34.4	34.7	36.5	30.4	27.2	21.5	22.0
+ 250 - 500	3.0	2.6	2.5	2.3	1.9	1.7	1.5	0.6	0.2	0.3
+ 125 - 250	0.1	0.1	0.1	0.1	0.1	0	0.1	0.2	0.1	0.1
+ 66 - 125	0.2	0.1	0.1	0.1	0	0	0.2	0.2	0.1	0.1
+ 45 - 66	0.1	0.1	0.1	0.1	0	0	0.1	0.1	0	0.1
- 45	0.1	0.1	0.1	0.1	0	0	0.1	0.1	0	0.1
Median diam. (μm)	1240	1230	1203	1211	1222	1192	1287	1321	1421	1396
Packed bulk density lb/ft^3	87.0	86.4	81.7	81.9	84.3	84.5	81.4	80.0	84.7	83.1

Table A.1.6.9a Flue gas analyses

Test No.			Datum	6.1				6.2			
Time from start (h)				0	1.5	3.5	Mean	0	2.5	3.5	**Mean**
Operating Conditions											
Ca/S mol ratio			0				2.5				5.4
Fluidising Velocity ft/s			8.0				8.0				8.0
Bed Temperature ^{o}F			1560				1560				1560
Bed Height ft.			2.7				2.7				2.7
Gas Analysis		Method									
Vol % dry gas	CO_2	Chromatograph	15.2	16.4	16.4	15.9	16.2	16.7	16.3	16.5	16.5
"	O_2		2.9	2.7	2.9	3.1	30.0	3.4	3.5	3.2	3.3
"	CO	"	0	0	0	0	0	0	0	0	0
"	CH_4	"	0	0	0	0	0	0	0	0	0
p.p.m.	NO_X	Saltzman's	{355 420				-	{420 365			390
"	SO_2	Iodine	2190				840				280
"	SO_2	I.R.A.					730				240
"	SO_2	H_2O_2					840				275
"	Cl	"					62				59
"	NH_3	"					4				9

Table A.1.6.9b Flue gas analyses

Test No.		6.3			6.4			6.5		
Time from start (h)		0	3	Mean	0	3	Mean	0.5	3	Mean
Operating Conditions										
Ca/S mol ratio				5.3			5.2			5
Fluidising Velocity ft/sec				8.1			8.0			8.0
Bed Temperature °F				1560			1560			1560
Bed Height				4.0			7			5.5
Gas Analysis	**Method**									
Vol % dry gas CO_2	Chromatograph	16.4	16.9	16.7	16.7	16.3	16.5	16.9	16.3	16.6
" O_2	"	3.5	3.3	3.4	2.7	2.7	2.7	2.8	3.3	3.0
" CO	"	0	0	0	0	0	0	0	0	0
" CH_4	"	0	0	0	0	0	0	0	0	0
p.p.m. NO_X	Saltzman's	305 415		360	410 385		400	405 450		425
" SO_2	Iodine			260			155			280
" SO_2	I.R.A.			190			115			160
" SO_2	H_2O_2			260			175			295
" Cl	"			59			55			60
" NH_3	"			15			7			12

Table A.1.6.10 Mass balance for Test 6.1

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium	Magnesium
Coal Feed	246.7	35.3	174.7	0	10.9	6.66	2.17	0
Acceptor Feed	100.0	64.7	0	0	0	0	21.10	13.10
Total Air	2505.7	0	0	1925	580.7	0	0	0
Total Input	2852.4	100.0	174.7	1925	591.5	6.66	23.27	13.10
Accumulated in bed	0	0	0	0	0	0.71	1.52	0.71
Offtake Ash	14.0	14.0	0	0	0	0.22	0.68	0.32
Primary Fines	118.0	95.3	22.66	0	0	3.60	23.01	13.10
Secondary Fines	4.4	4.2	0.18	0	0	0.22	0.53	0.26
Exhaust Dust	2.0	1.9	0.07	0	0	0.13	0.25	0.12
Flue Gas	2729.3	0	154.2	1932	589.9	2.22	0	0
Total Output	2867.7	115.4	177.1	1932	589.9	7.10	25.99	14.51
Loss (in - Out)	- 15.3	-15.4	- 2.4	-7	1.6	- 44	-2.72	-1.41
Loss Percent	-0.5	-15.4	- 1.4	-0.4	0.3	-6.4	-11.7	-10.8

Excess air	4.0%
Carbon loss	12.9% (Unburnt)
Sulphur retention	67%
Ca/S mol ratio	2.5

Table A.1.6.11 Mass balance for Test 6.2

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium	Magnesium
Coal Feed	243.8	34.9	172.6	0	10.7	6.34	2.15	0
Acceptor Feed	202.0	126.7	0	0	0	0	42.62	26.46
Total Air	2501.8	0	0	1922	579.8	0	0	0
Total Input	2947.6	161.6	172.6	1922	590.5	6.34	44.77	26.46
Accumulated in bed	0	0	0	0	0	0.54	1.68	0.79
Offtake Ash	15.5	15.5	0	0	0	0.52	1.45	0.68
Primary Fines	165.0	143.1	21.95	0	0	4.87	40.59	24.10
Secondary Fines	6.0	5.9	0.14	0	0	0.32	1.00	0.53
Exhaust Dust	2.9	2.8	0.05	0	0	0.24	0.39	0.21
Flue Gas	2758.7	0	149.0	1937	579.9	0.74	0	0
Total Output	2948.1	167.3	171.1	1937	579.9	7.23	45.11	26.31
Loss (In - Out)	-0.5	-5.7	1.5	-15	10.6	-0.89	-0.34	0.15
Loss Percent	0	-3.5	0.9	-0.8	1.8	-14.1	-0.8	0.6

Excess air	5.5%	
Carbon loss	12.9%	(Unburnt)
Sulphur retention	88%	
Ca/S mol ratio	5.4	

Table A.1.6.12 Mass balance for Test 6.3

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium	Magnesium
Coal Feed	252.6	36.1	178.9	0	11.1	6.57	2.22	0
Acceptor Feed	205.0	124.2	0	0	0	0	43.25	26.9
Total Air	2513.5	0	0	1931	582.5	0	0	0
Total Input	2971.1	160.3	178.9	1931	593.6	6.57	45.47	26.9
Accumulated in bed	0	0	0	0	0	0.16	0.78	0.31
Offtake Ash	0	0	0	0	0	0	0	0
Primary Fines	177.0	150.8	26.20	0	0	4.96	46.02	24.60
Secondary Fines	7.0	6.7	0.26	0	0	0.42	1.25	0.64
Exhaust Dust	4.8	4.7	0.08	0	0	0.43	0.65	0.36
Flue Gas	2778.5	0	150.5	1939	590.5	0.69	0	0
Total Output	2967.3	162.2	177.0	1939	590.5	6.66	48.70	25.91
Loss (In - Out)	3.8	- 1.9	1.9	-8	3.1	-0.09	-3.23	0.99
Loss Percent	0.1	- 1.2	1.1	-0.4	0.5	-1.3	-7.1	3.7

Excess air	3.7%
Carbon loss	15.0% (Unburnt)
Sulphur retention	90%
Ca/S mol ratio	5.3

Table A.1.6.13 Mass balance for Test 6.4

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium	Magnesium
Coal Feed	255.6	36.5	181.0	0	11.2	6.65	2.25	0
Acceptor Feed	203.0	122.2	0	0	0	0	42.83	26.60
Total Air	2509.6	0	0	1928	581.6	0	0	0
Total Input	2968.2	158.7	181.0	1928	592.8	6.65	45.08	26.60
Accumulated in bed	-34.9	-34.9	0	0	0	-0.38	0.23	-0.52
Offtake Ash	0	0	0	0	0	0	0	0
Primary Fines	210	182.3	27.72	0	0	5.25	41.58	24.57
Secondary Fines	9.0	8.8	0.21	0	0	0.69	1.75	1.04
Exhaust Dust	7.2	7.1	0.08	0	0	0.75	1.22	0.66
Flue Gas	2772.2	0	149.2	1955	569.2	0.41	0	0
Total Output	2963.5	163.3	177.2	1955	569.2	6.73	44.78	25.75
Loss (In - Out)	4.7	-4.6	3.8	- 27	23.6	-0.08	0.3	0.85
Loss Percent	0.2	-2.9	2.1	-1.4	4.0	-1.2	0.7	3.2

Excess air	0%	
Carbon loss	15.5%	(Unburnt)
Sulphur retention	94%	
Ca/S mol ratio	5.2	

Table A.1.6.14 Mass balance for Test 6.5

Rate: lb/h	Total	'Ash'	'Carbon'	Nitrogen	'Oxygen'	Sulphur	Calcium	Magnesium
Coal Feed	252.6	36.1	178.9	0	11.1	6.82	2.22	0
Acceptor Feed	203.0	122.2	0	0	0	0	42.83	26.60
Total Air	2501.8	0	0	1922	579.8	0	0	0
Total Input	2957.4	158.3	178.9	1922	590.9	6.82	45.05	26.60
Accumulated in bed	0	0	0	0	0	0.14	0.86	0
Offtake Ash	0	0	0	0	0	0	0	0
Primary Fines	186.5	159.5	27.04	0	0	4.94	44.2	24.99
Secondary Fines	9.9	9.6	0.31	0	0	0.76	1.98	1.11
Exhaust Dust	7.0	6.9	0.08	0	0	0.74	1.20	0.64
Flue Gas	2764.7	0	148.8	1942	575.0	0.74	0	0
Total Output	2968.1	176.0	176.2	1942	575.0	7.32	48.24	26.74
Loss (In - Out)	-10.7	-17.7	2.7	-20	15.9	-0.50	-3.19	-0.14
Loss Percent	-0.4	-11.2	1.5	-1.0	2	-7.4	-7.1	-0.5

Excess air	1.3%	
Carbon loss	15.6%	(Unburnt)
Sulphur retention	89%	
Ca/S mol ratio	5.0	

Table A.1.6.15 Pressure drops through the combustor

Test No.	6.1	6.2	6.3	6.4	6.5
Fluidising Velocity ft/s	8.0	8.0	8.1	8.0	8.0
Bed Height ft.	2.7	2.7	4.0	7.3-6.4	5.5
	Pressure drop, inches w.g.				
Baseplate	34	34	33	32	32
Bed	21	19	30	67-59	50
Density (over 8 ins)	5.2	4.8	5.0	6.1	6.1
1° Cyclone	2.5	2.5	2	4	2
2° Cyclone	14	14	13	11	13

Table A.1.6.16 Temperature distribution through the combustor

Test			6.1	6.2	6.3	6.4	6.5
Fluidising Velocity ft/s			8.0	8.0	8.1	8.0	8.0
Bed Height ft			2.7	2.7	4.0	6.9	5.5
Excess Air %			4.0	5.5	3.7	0	1.3
Probe Number	Height above bubble caps (ins)	Projection into combustor (ins)	Temperature °F				
N2	4	3	1546	1539	1539	1522	1526
N14	4	9	1578	1561	1567	1562	1569
N3	12	3	1589	1589	1584	1571	1584
N4	12	9	1582	1575	1569	1569	1578
N15	12	3	1558	1558	1566	1558	1562
N5	20	9	1540	1551	1558	1569	1578
N6	27	3	1575	1576	1587	1589	1526
N16	27	9	1567	1564	1580	-	-
N7	39	9	1593	1593	1589	-	1594
N19	39	9	1593	1589	1580	1593	1607
N20	50	9	1593	1591	1598	-	1488
N21	50	9	1602	1605	1589	-	-
N9	94	9	1481	1490	1500	1602	1571
N23	94	9	1648	1638	1629	1620	1636
N10	130	9	1585	1605	1557	1582	1580
N24	130	3	1616	1627	1593	1580	1591
N25	130	9	1560	1575	1596	1602	1611
N11	154	9	1580	1593	1584	1589	1594
N27	154	9	1531	1540	1567	1584	1585
1° Cyclone			1391	1573	1400	1405	1409
2° Cyclone			1452	1459	1454	1449	1454
Steam to Freeboard lb/hr			300	250	0	50	50

Table A.1.6.17 SO_2 concentrations and % reductions

Test No.	Datum	6.1	6.2	6.3	6.4	6.5
Fluidising Velocity, ft/s	8	8	8	8	8	8
Bed Temperature, °F	1560	1560	1560	1560	1560	1560
Bed Height, ft	2.7	2.7	2.7	4.0	7.3-6.4	5.5
Ca/S mol ratio	0	2.5	5.4	5.3	5.2	5.0
SO_2 concentration, p.p.m.	2190	840	280	260	155	280
SO_2 reduction, %	0	62	87	88	93	87

Table A.1.6.18 SO_2 concentrations and % reductions during temperature survey

Time, mins	Bed Temperature, °F	SO_2 concentrations p.p.m.	SO_2 reduction %
0	1550	240	88
10	1560	240	88
20	1637	510	74
28	1595	290	85
33	1627	360	81
40	1505	175	91
50	1477	150	92.3
60	1450	125	93.5
80	1420	125	93.5
90	1460	90	93.5
100	1525	125	93.5
110	1560	200	90
120	1560	175	91

The datum SO_2 concentration for the infra-red analyser was taken as 1950 p.p.m.

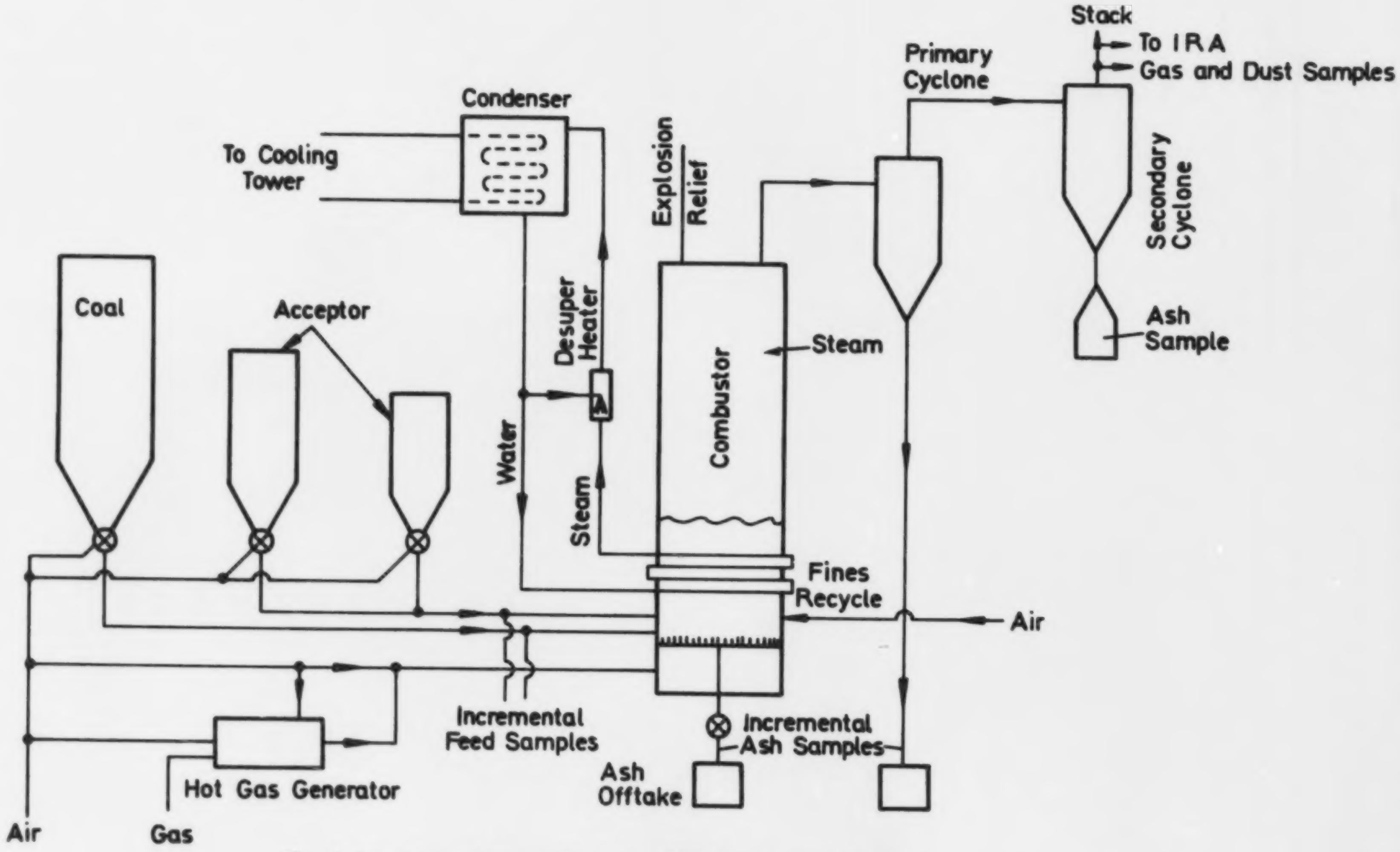


Fig. A.1.1. General Flow Diagram. 36" Combustor Plant.

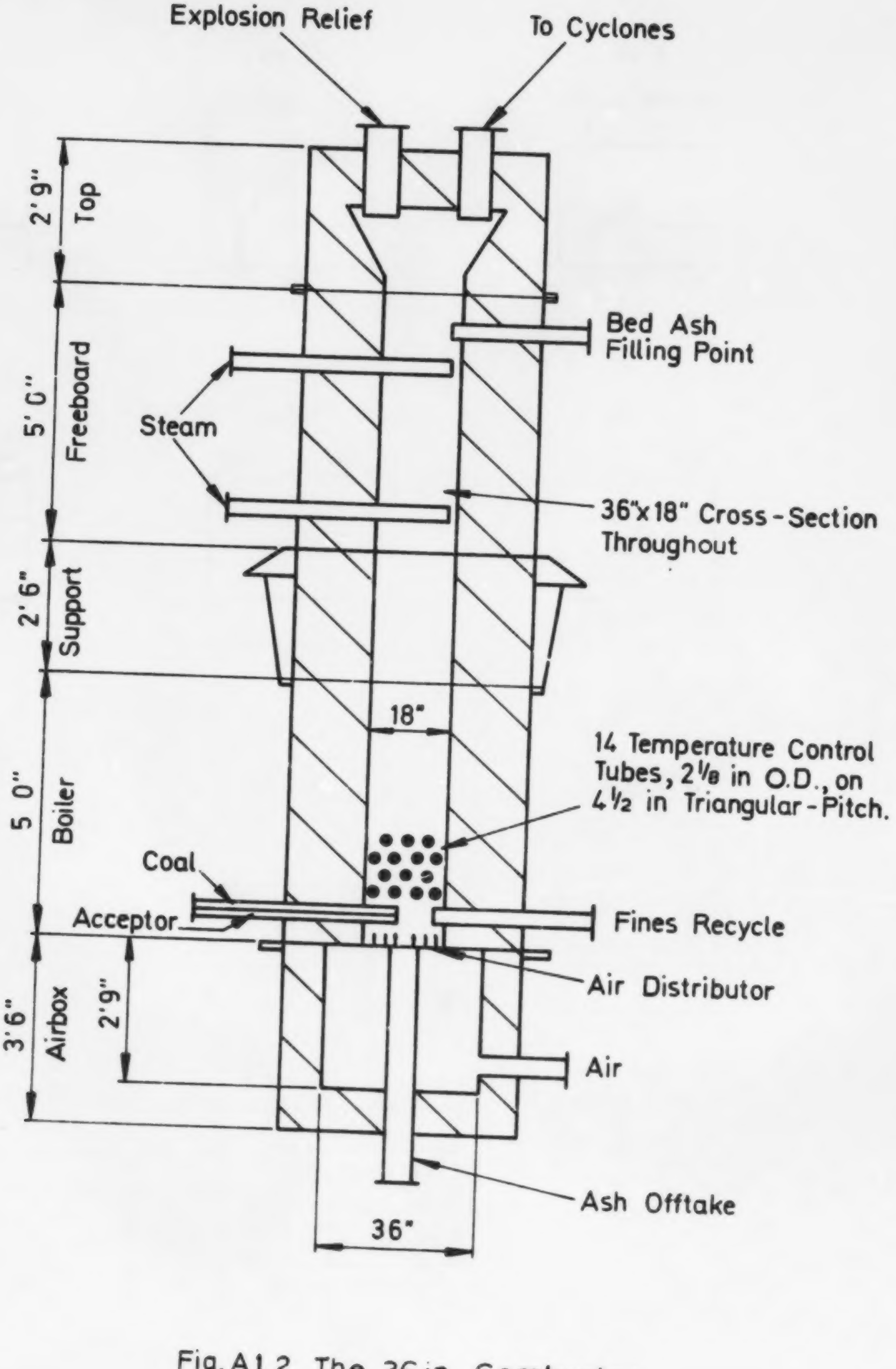
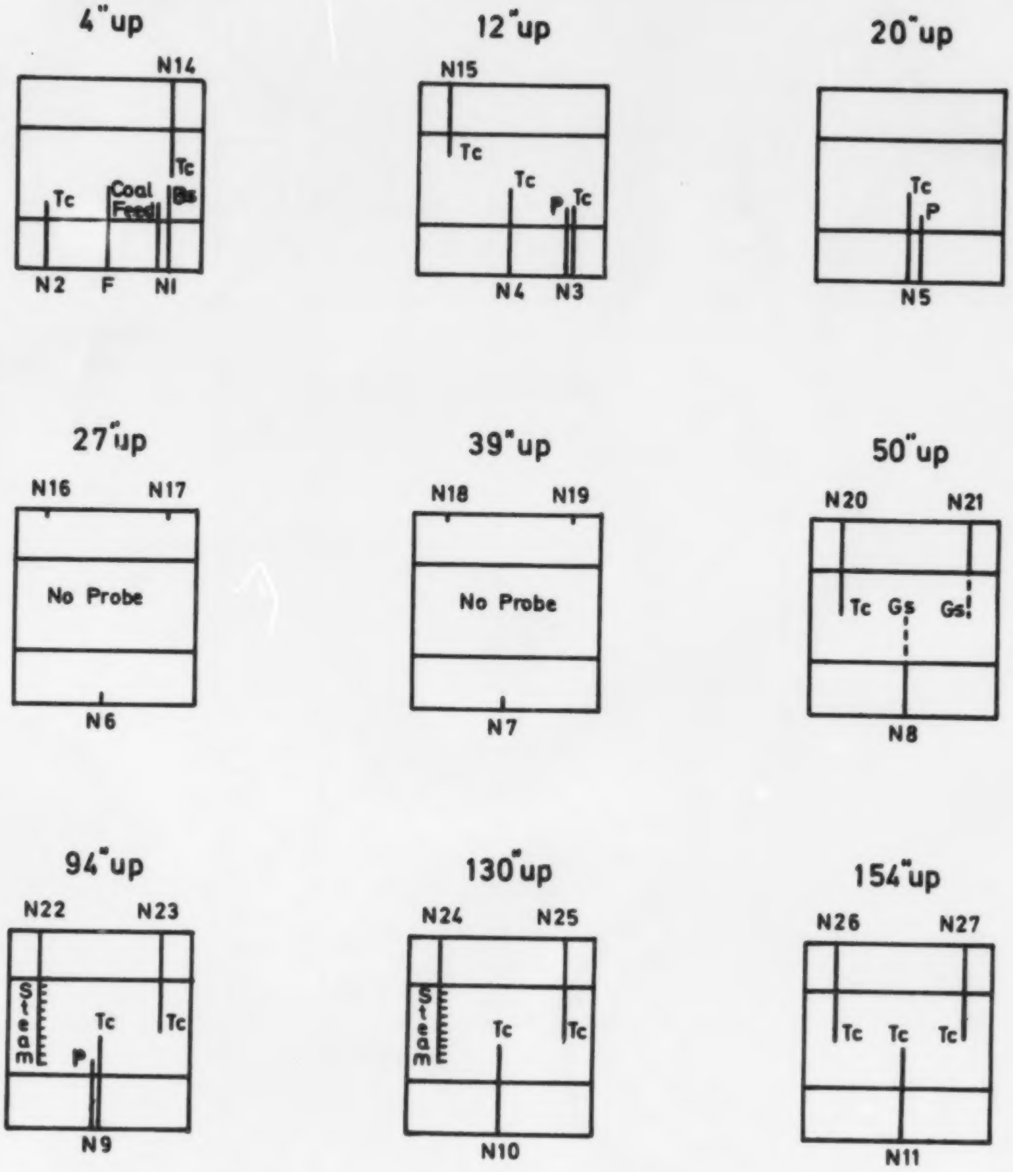


Fig. A1.2. The 36in. Combustor



Key	
Thermocouple	TC
Bed Ash Sampler	BS
Gas Sampler	GS
Pressure probe	P

Fig. A.1.3 Cross-sections of 36in combustor at varying heights above air jets showing typical positions of probes etc.

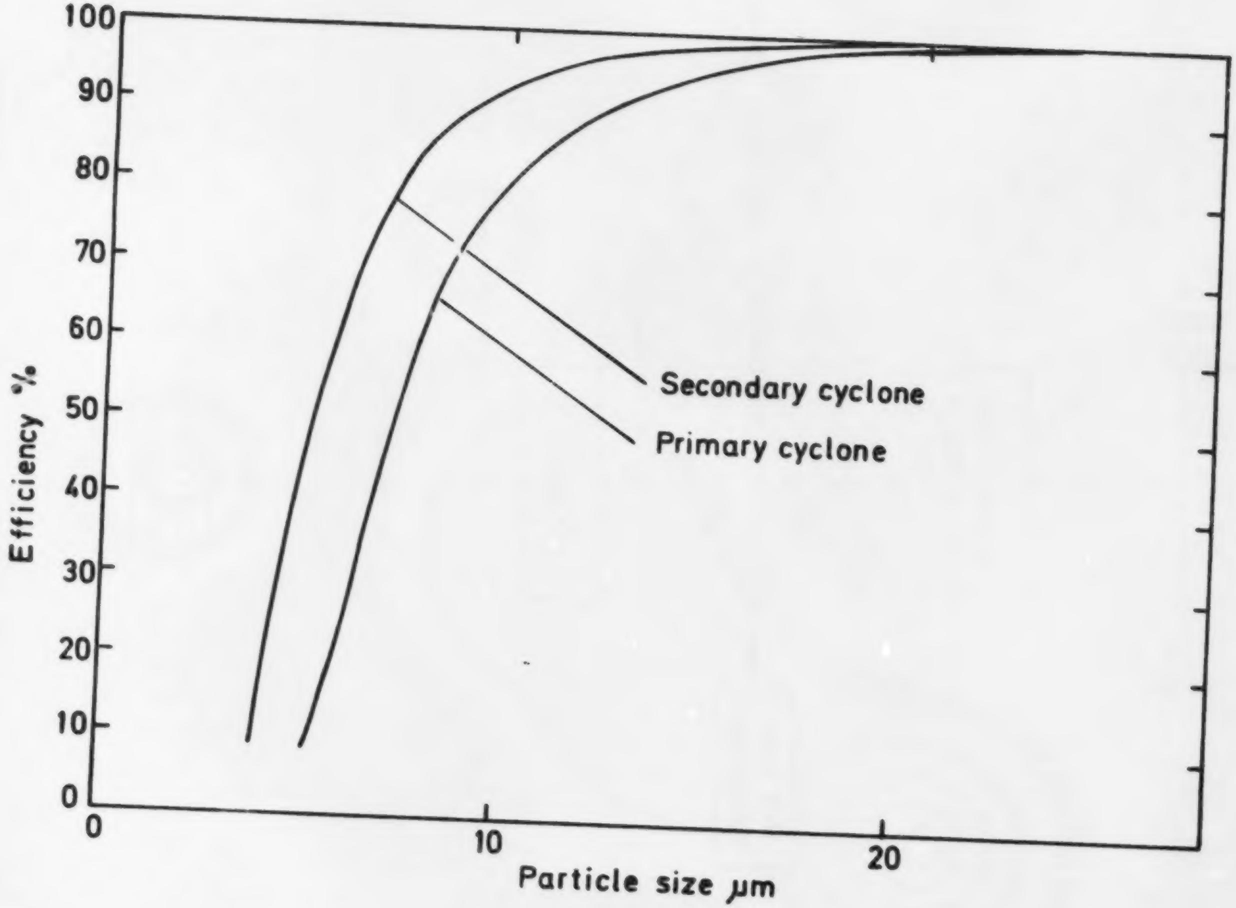


Fig. A.1.4. Efficiencies of the primary and secondary cyclones

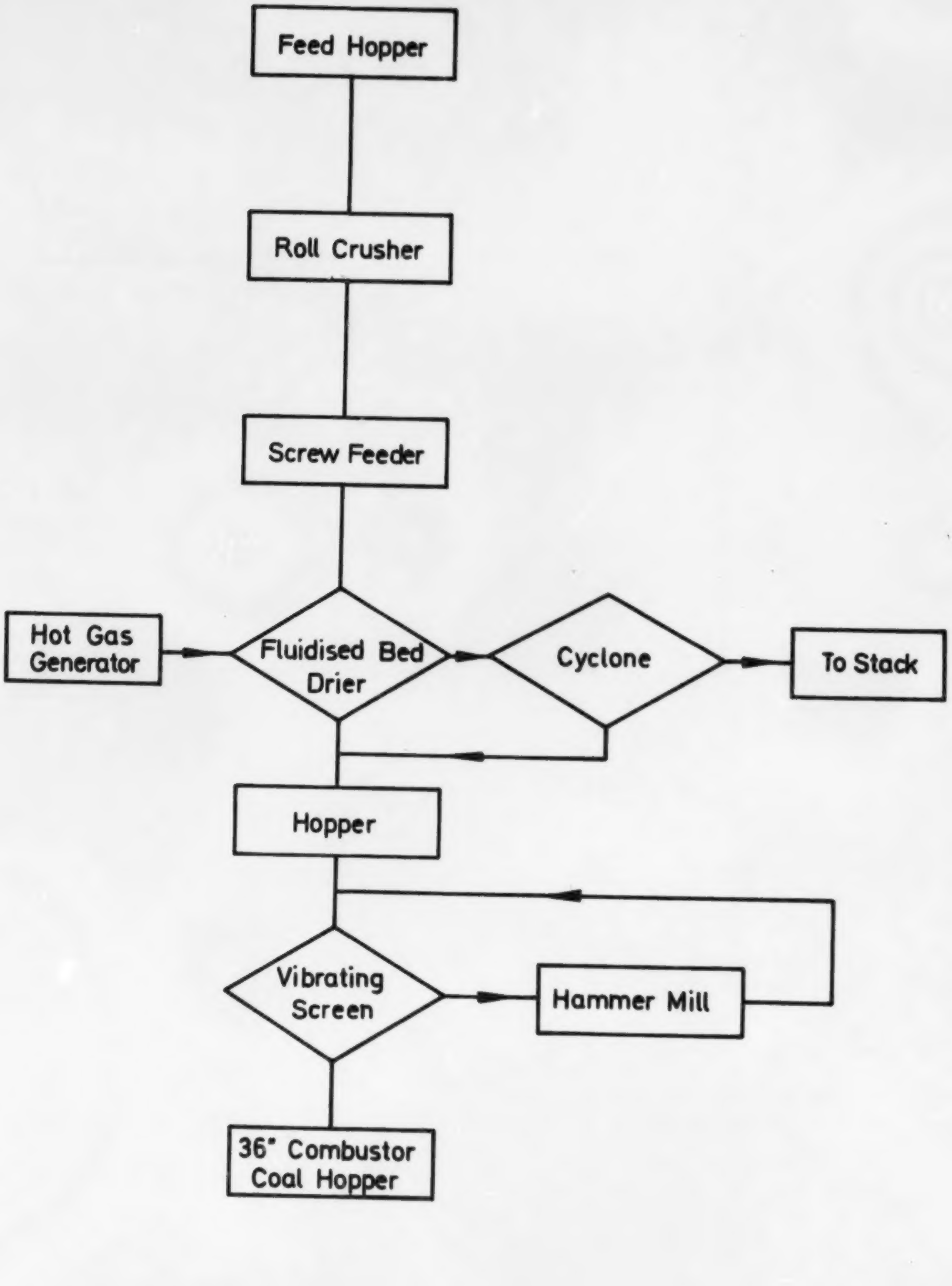


Fig. A 1.5. The Fluostatic Drier / Sample House Crusher System Used For Coal Preparation.

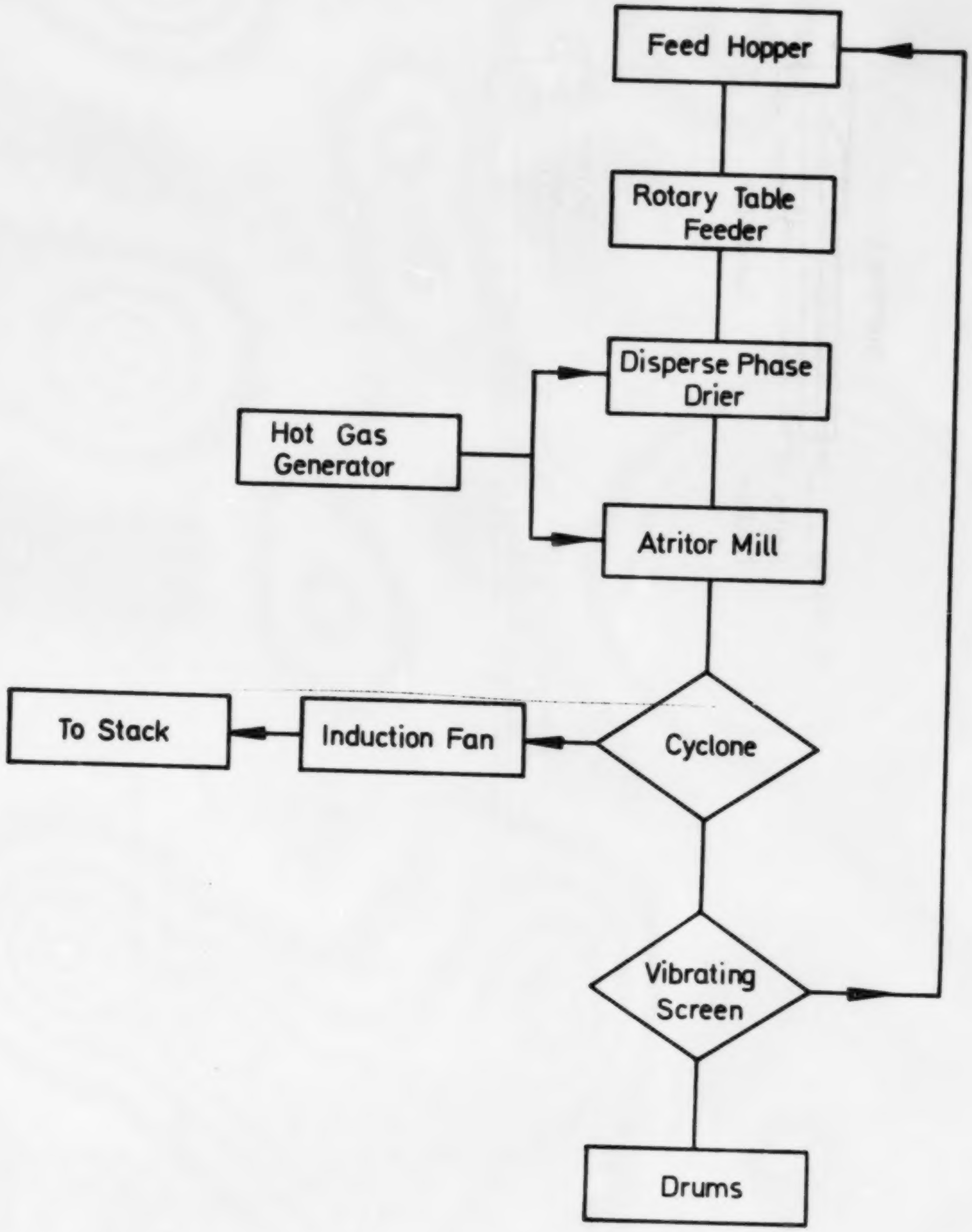


Fig. A 1.6. The Atritor Plant Used For Limestone And Dolomite Preparation.

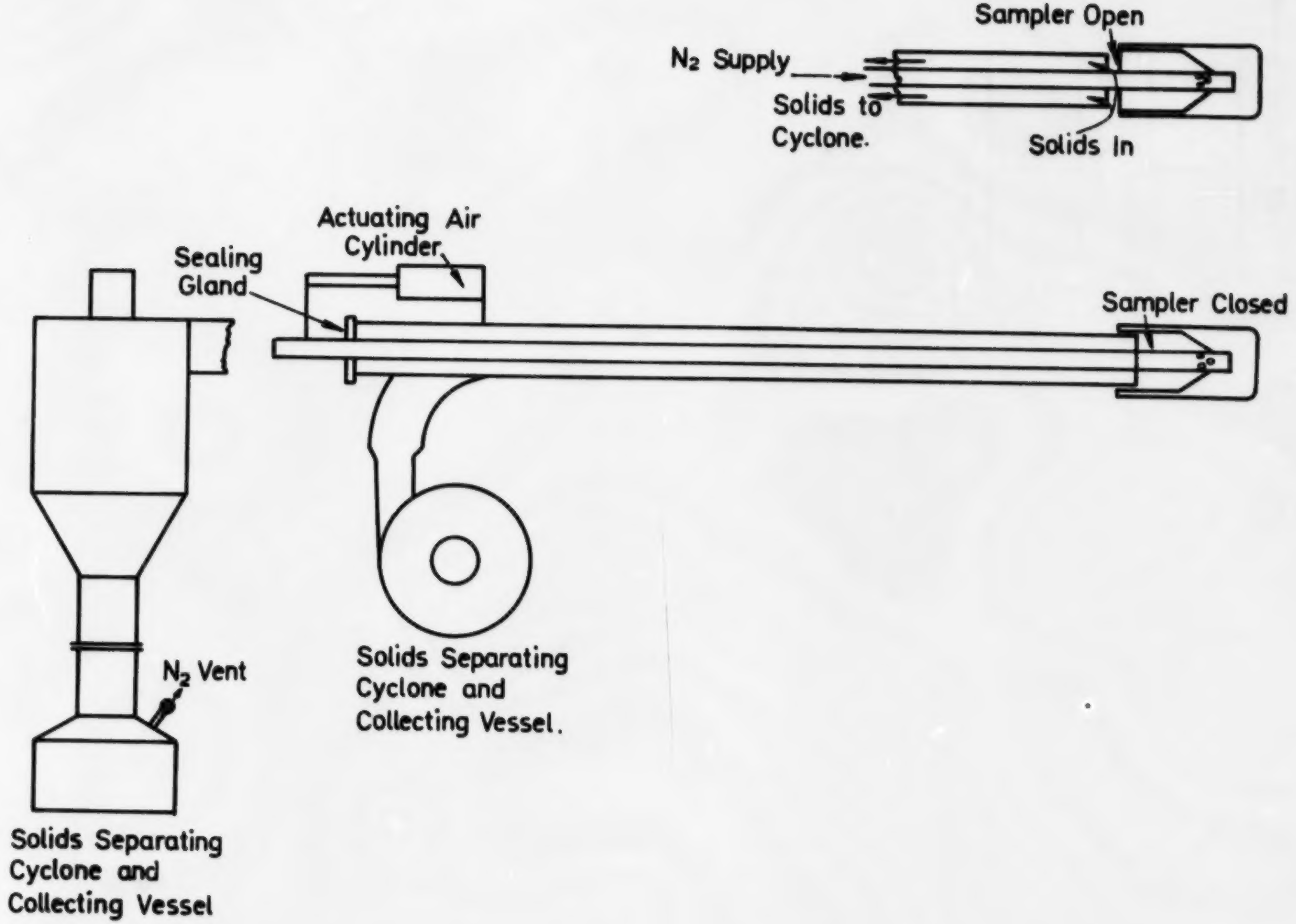


Fig. A.1.7. Apparatus for sampling the solids in the fluidised bed.

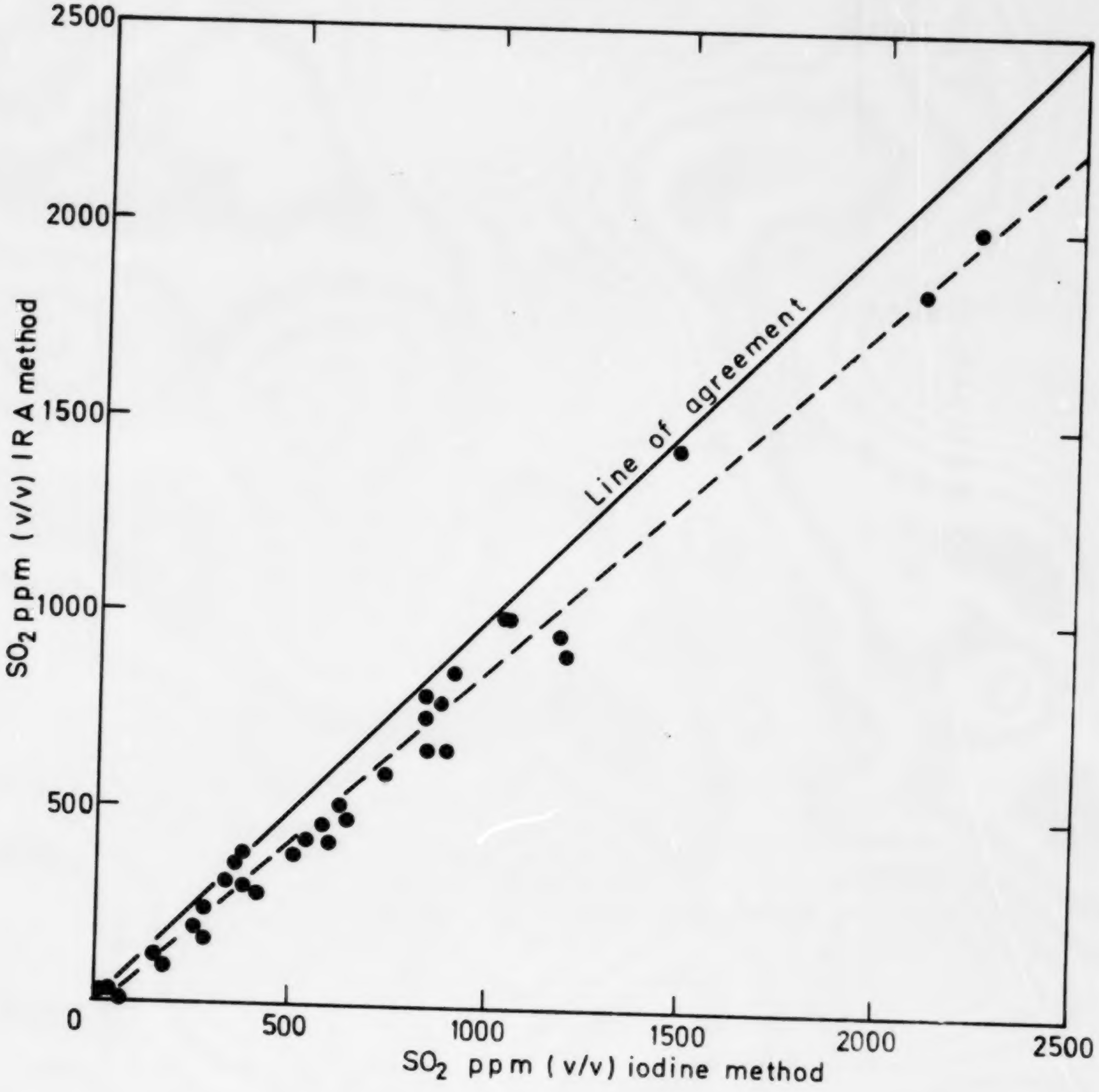


Fig. A1. 8. Comparison of SO_2 results from two methods of analysis

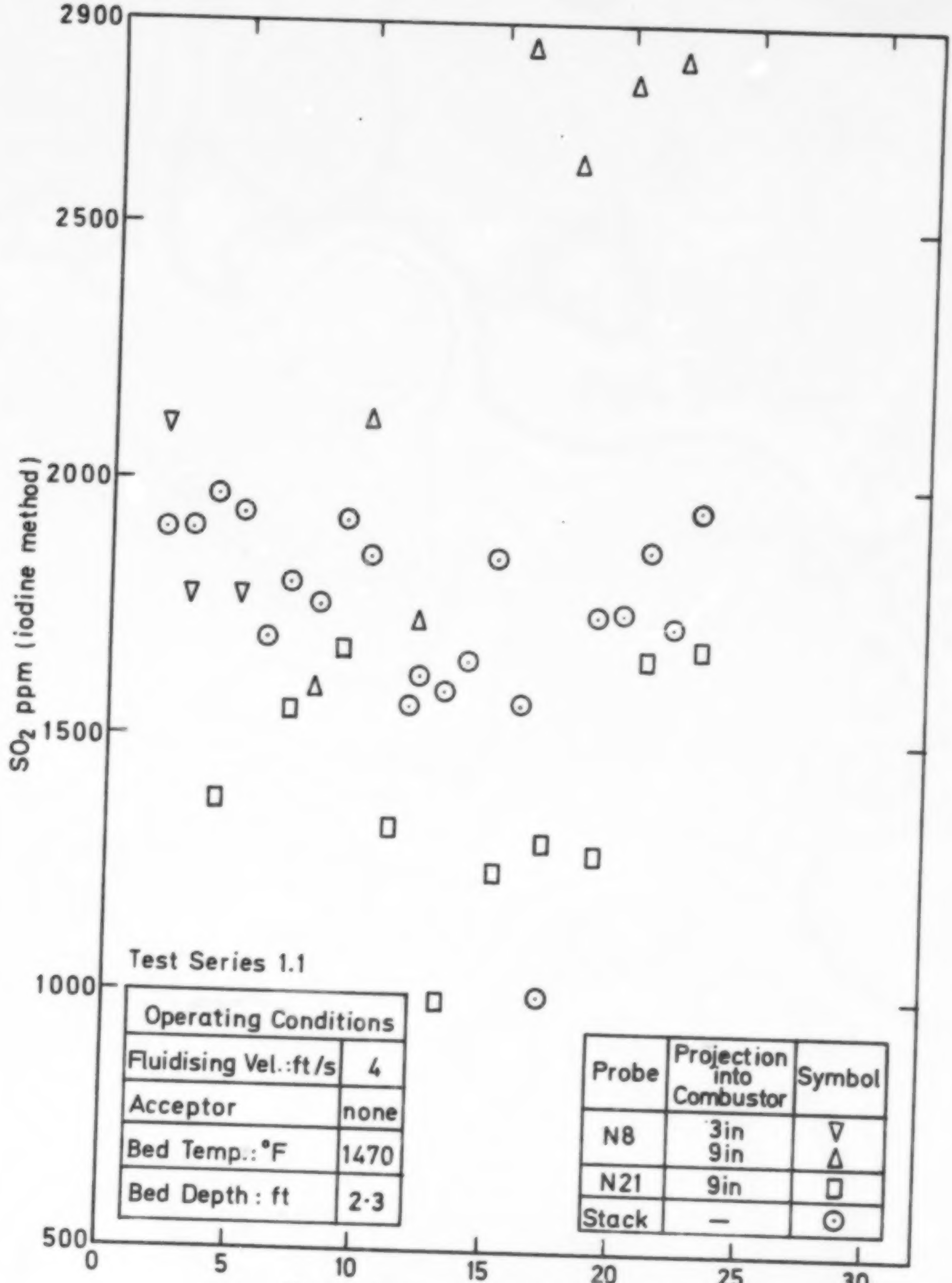


Fig. A1.1.1. Variation in SO$_2$ concentration (iodine method) with time and sampling position in Test Series 1.1

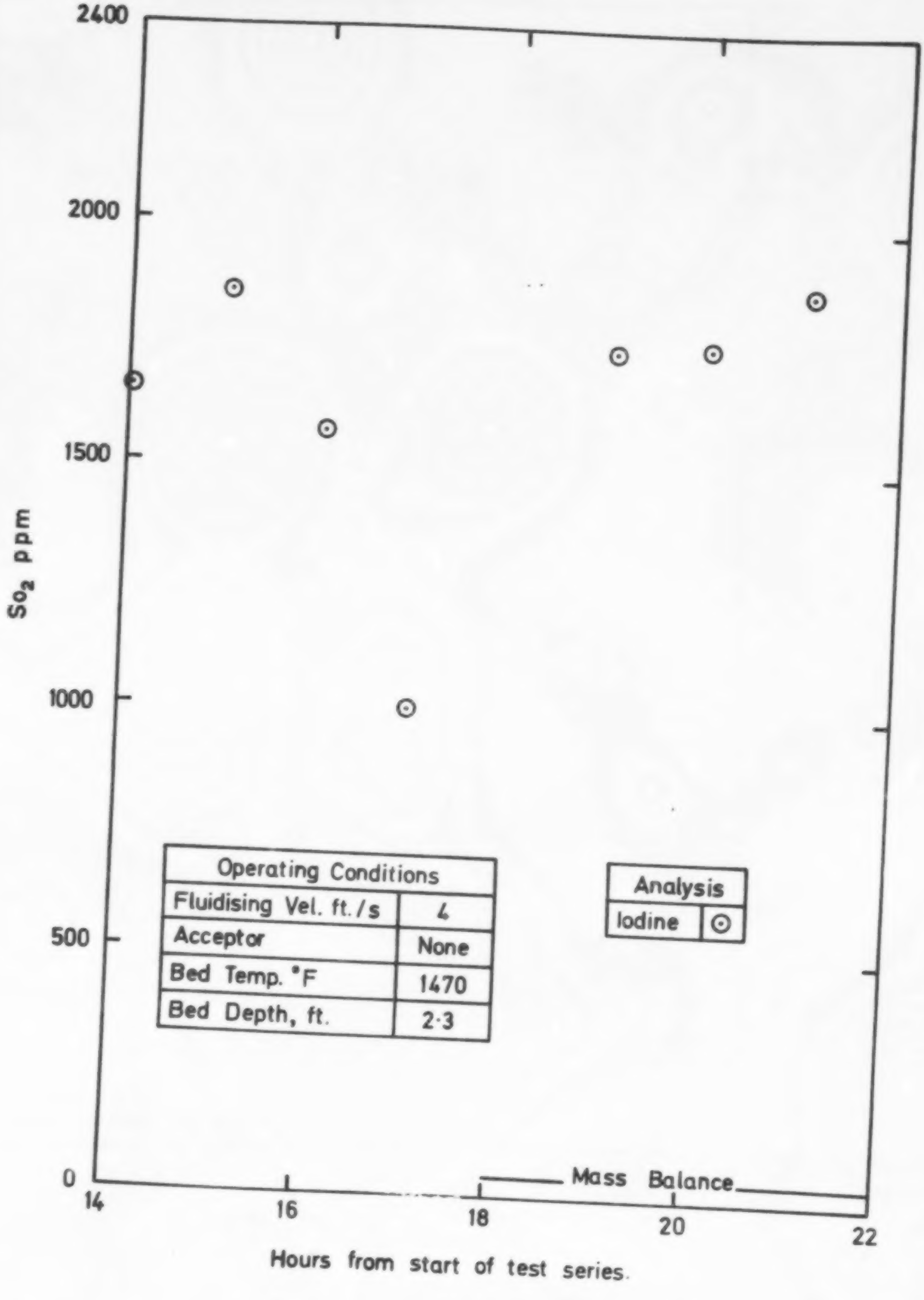


FIG. A.1.1.2. SO_2 concentrations in Test 1·1

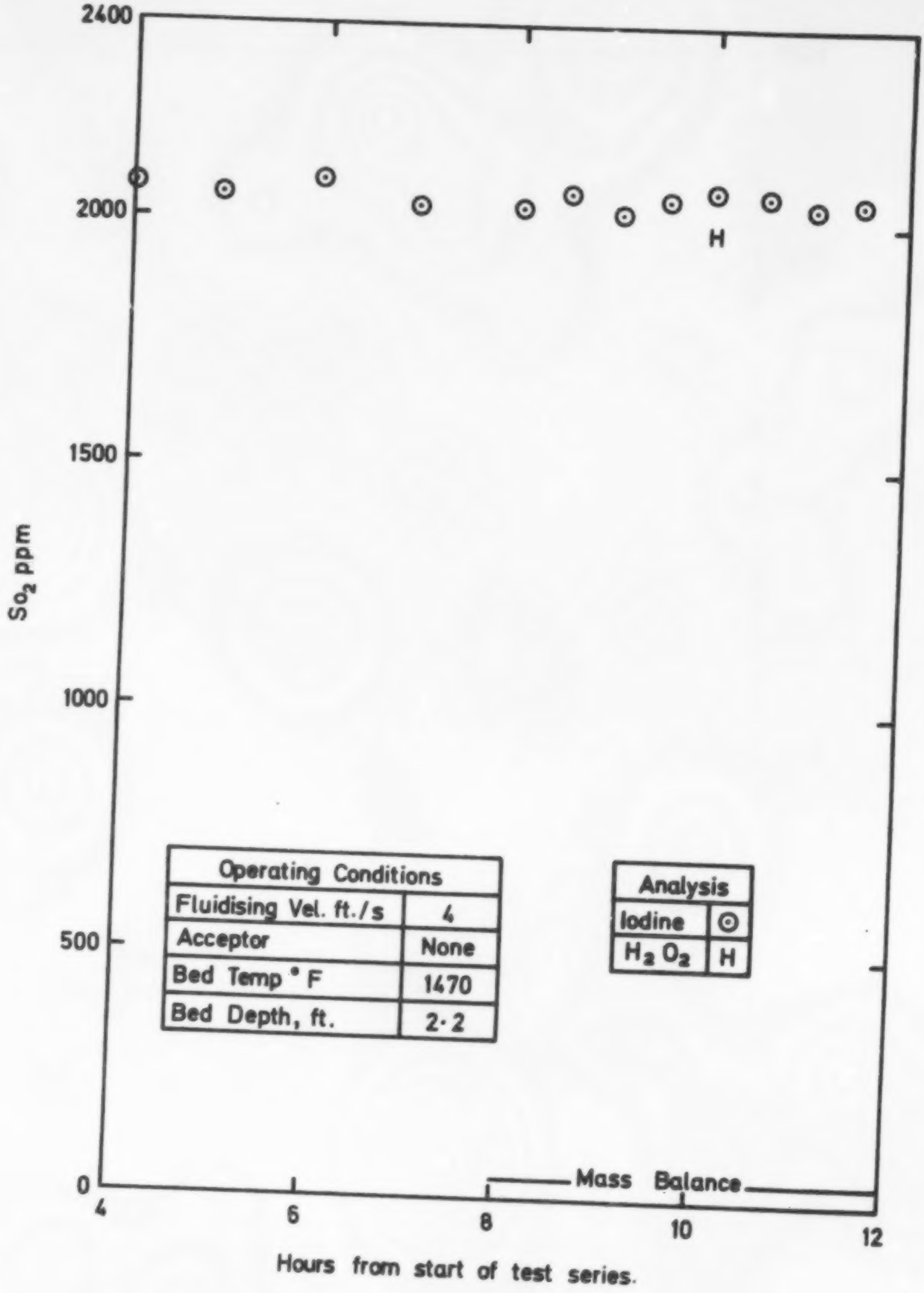


Fig. A.1.1.3. SO_2 concentrations in Test 1·2

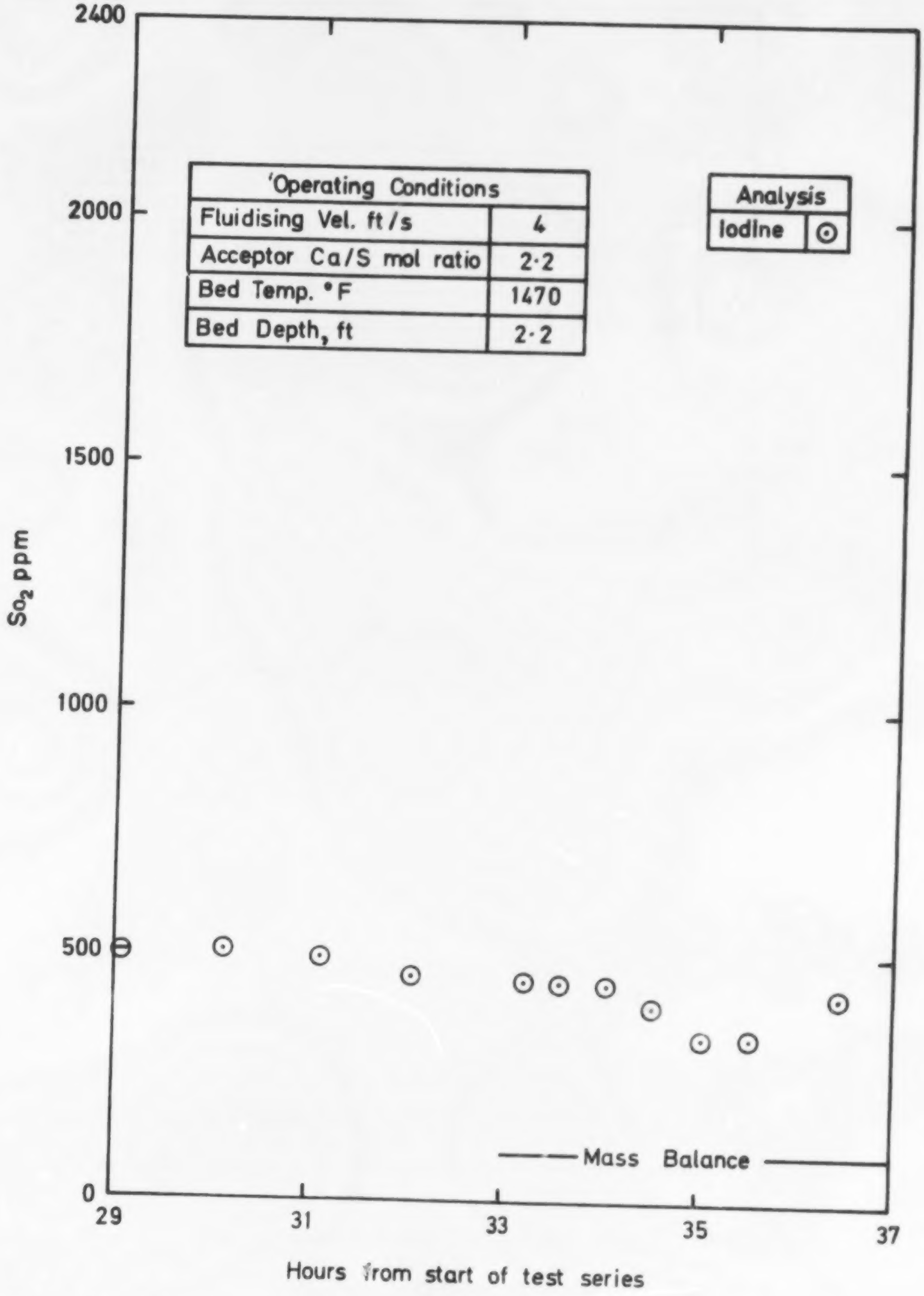


Fig. A 1.1.4. So$_2$ concentrations in Test 1·3

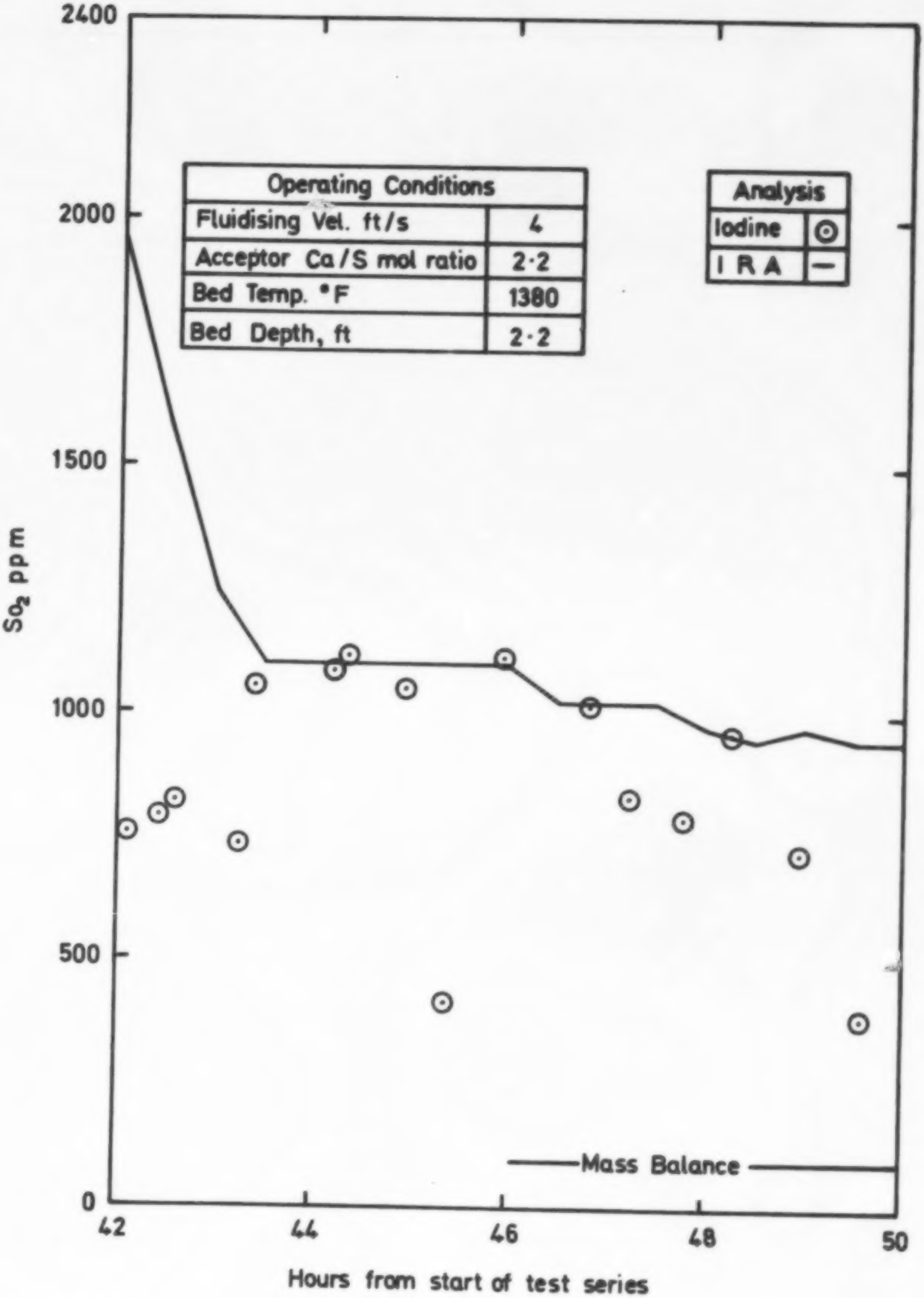


Fig. A 1.1.5. SO_2 concentrations in Test 1·4

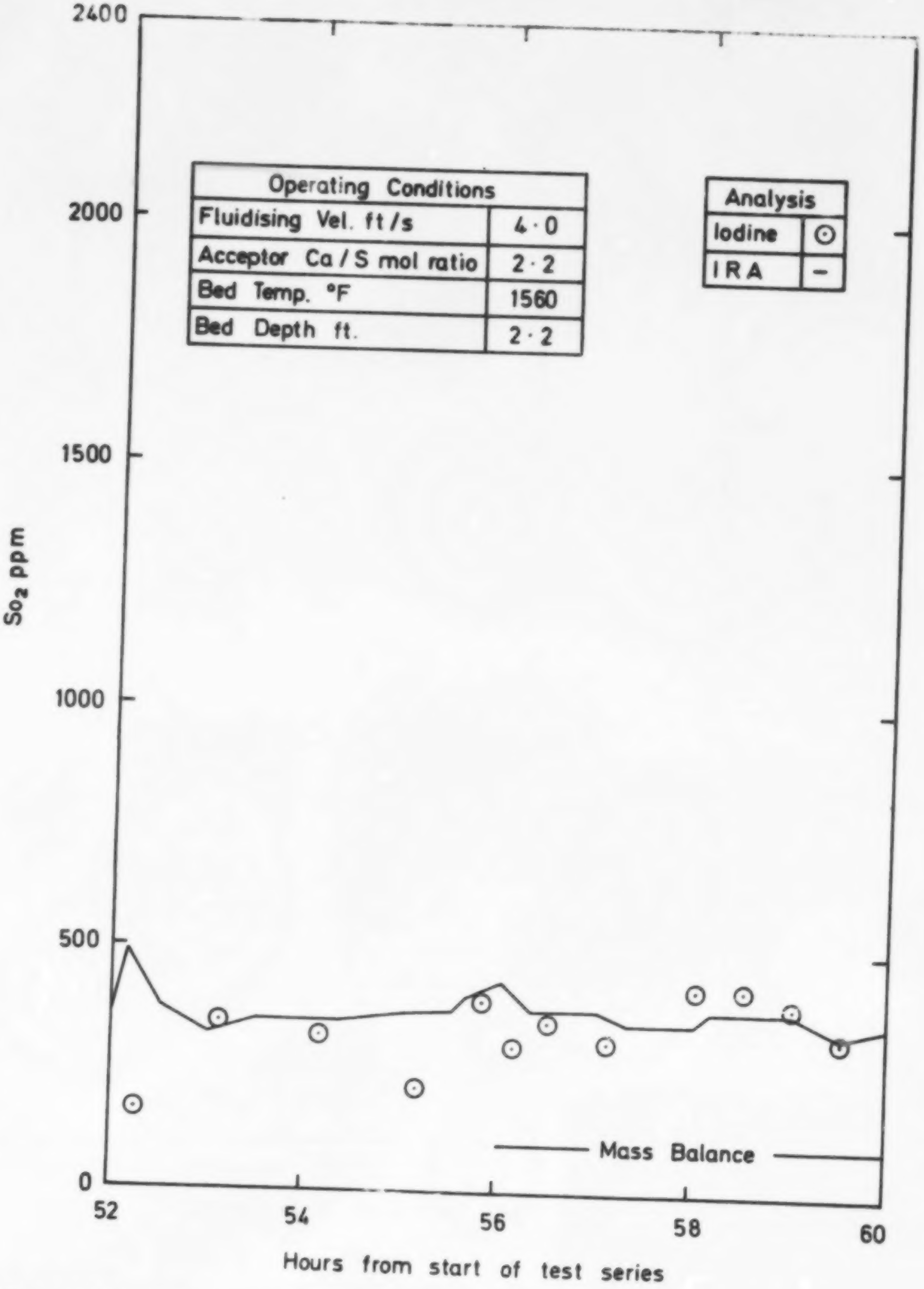
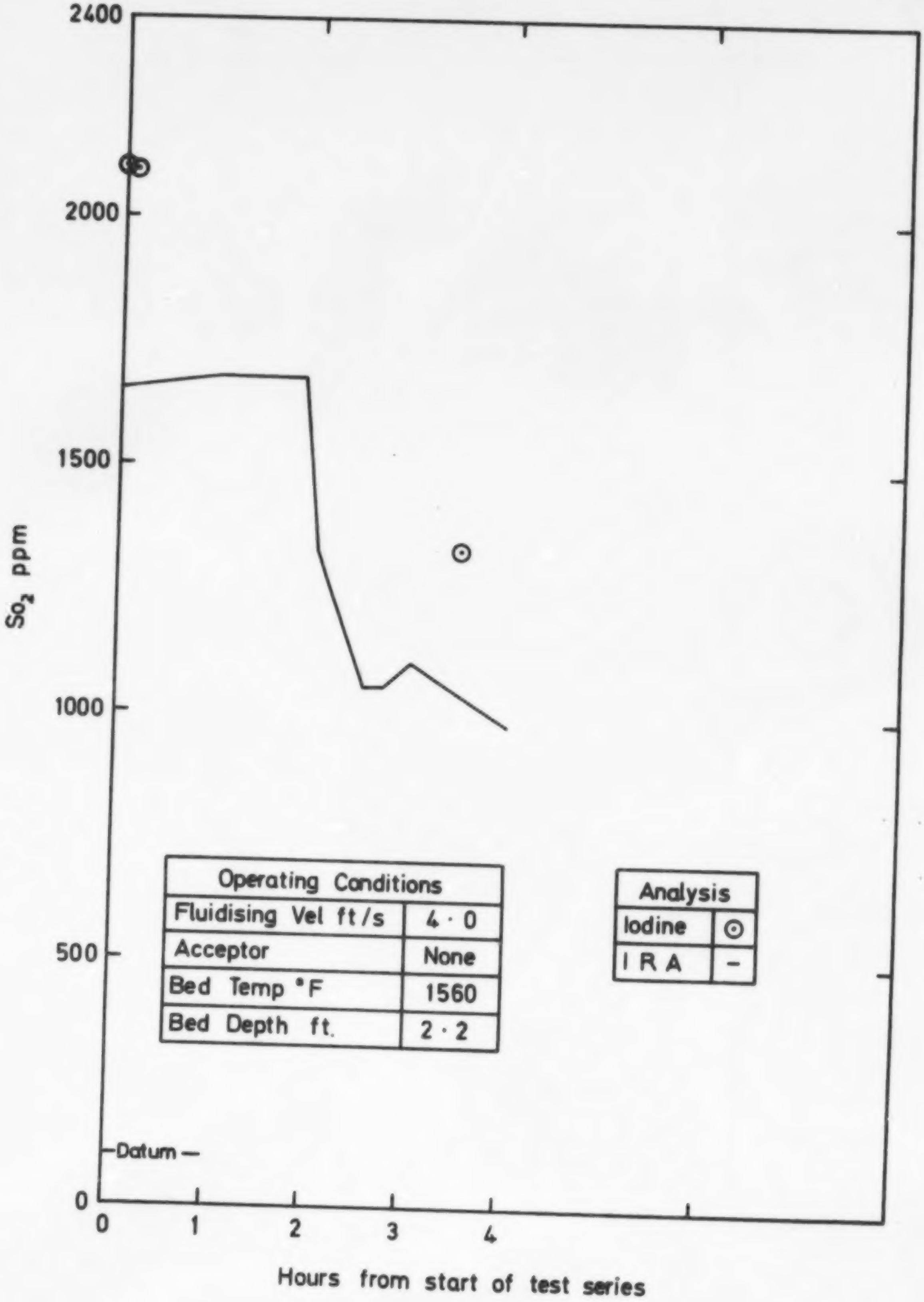


Fig. A 1.1.6. SO_2 concentrations in Test 1·5



Operating Conditions	
Fluidising Vel ft/s	4 · 0
Acceptor	None
Bed Temp °F	1560
Bed Depth ft.	2 · 2

Analysis	
Iodine	⊙
I R A	–

Fig. A.1.1.7. Datum SO_2 concentration for Tests 1·6 to 1·9

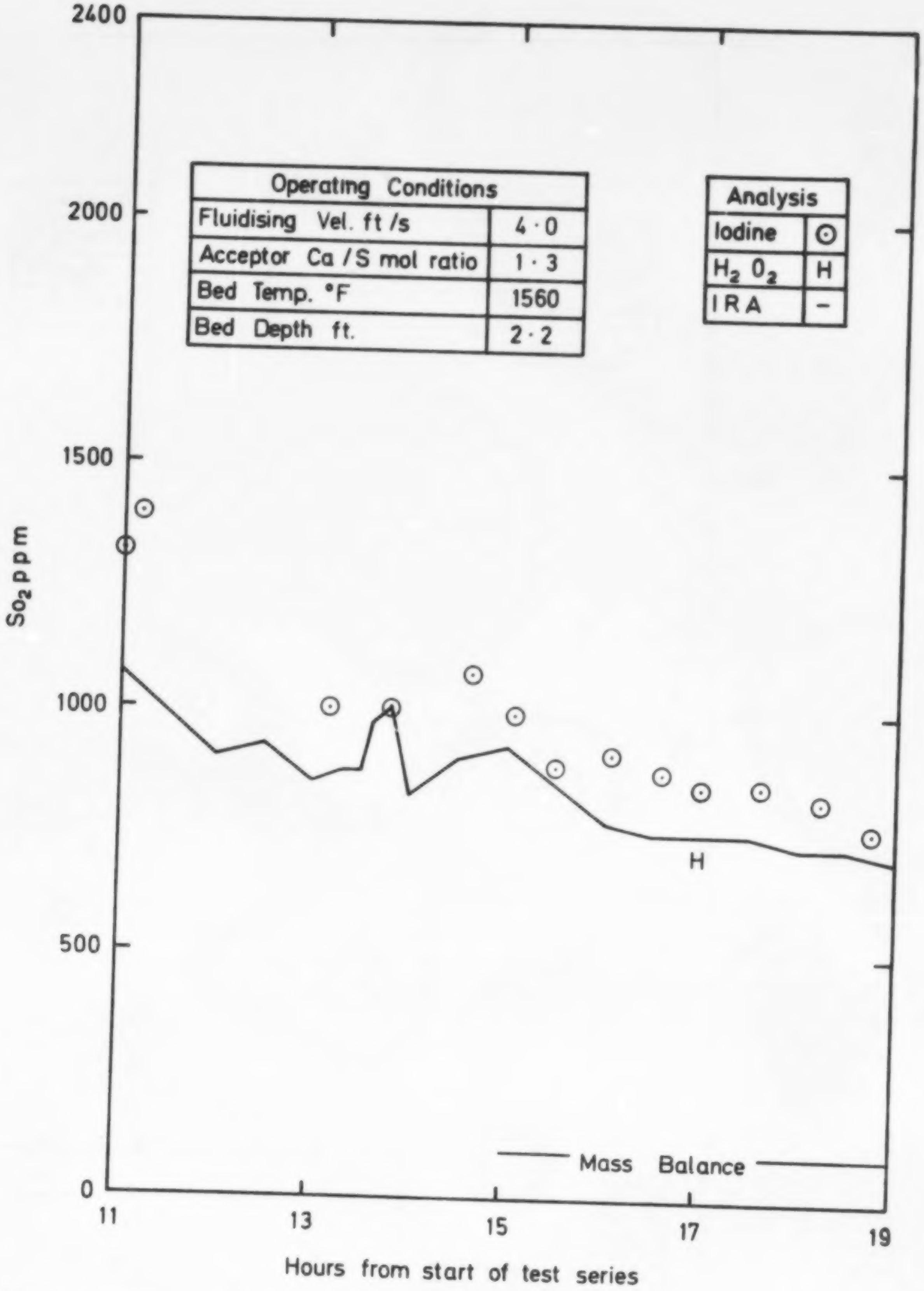


Fig. A 1.1.8. SO_2 concentrations in Test 1·6

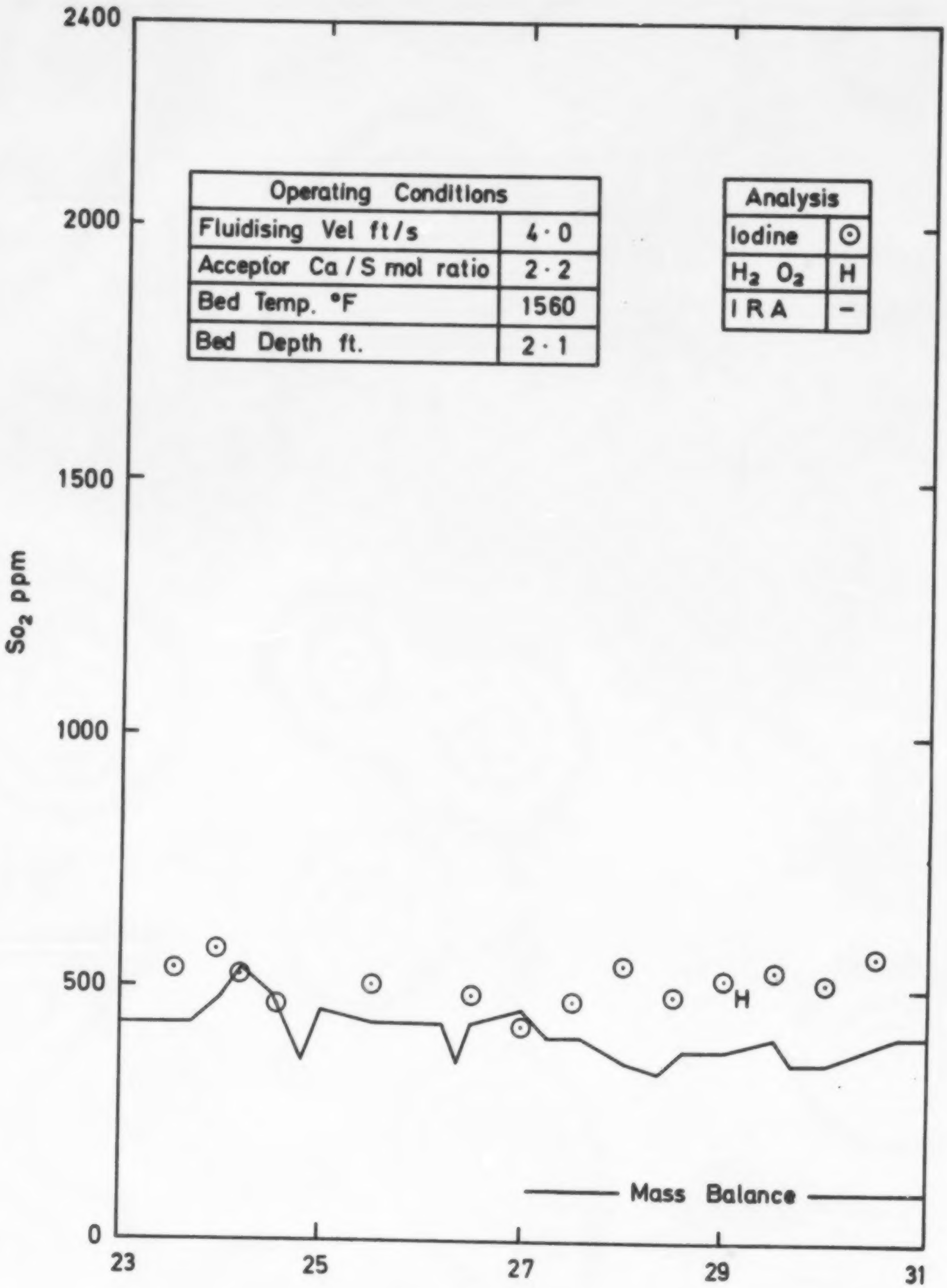


Fig. A 1.1.9. So$_2$ concentrations in Test 1 · 7

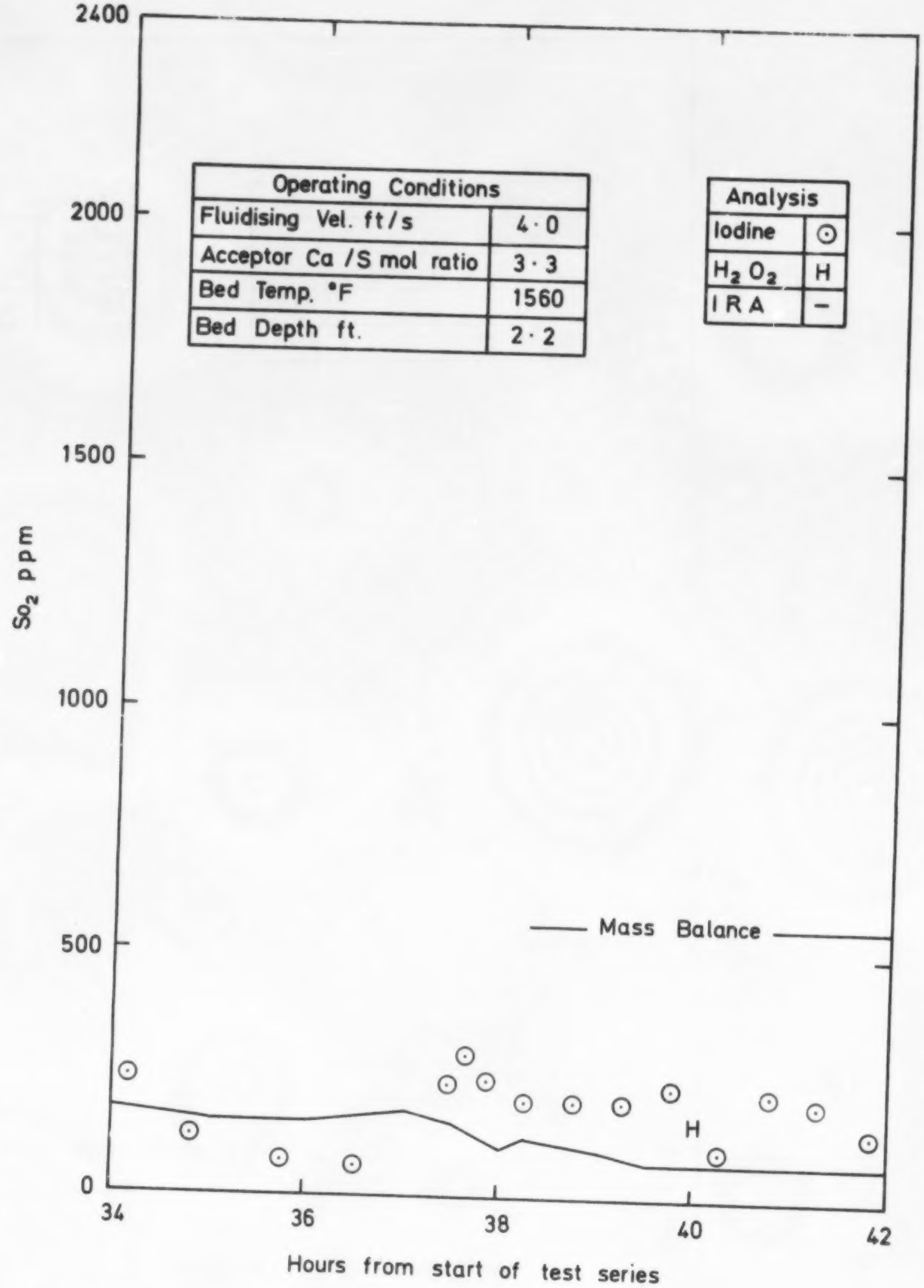


Fig. A 1.1.10. So$_2$ concentrations in Test 1·8

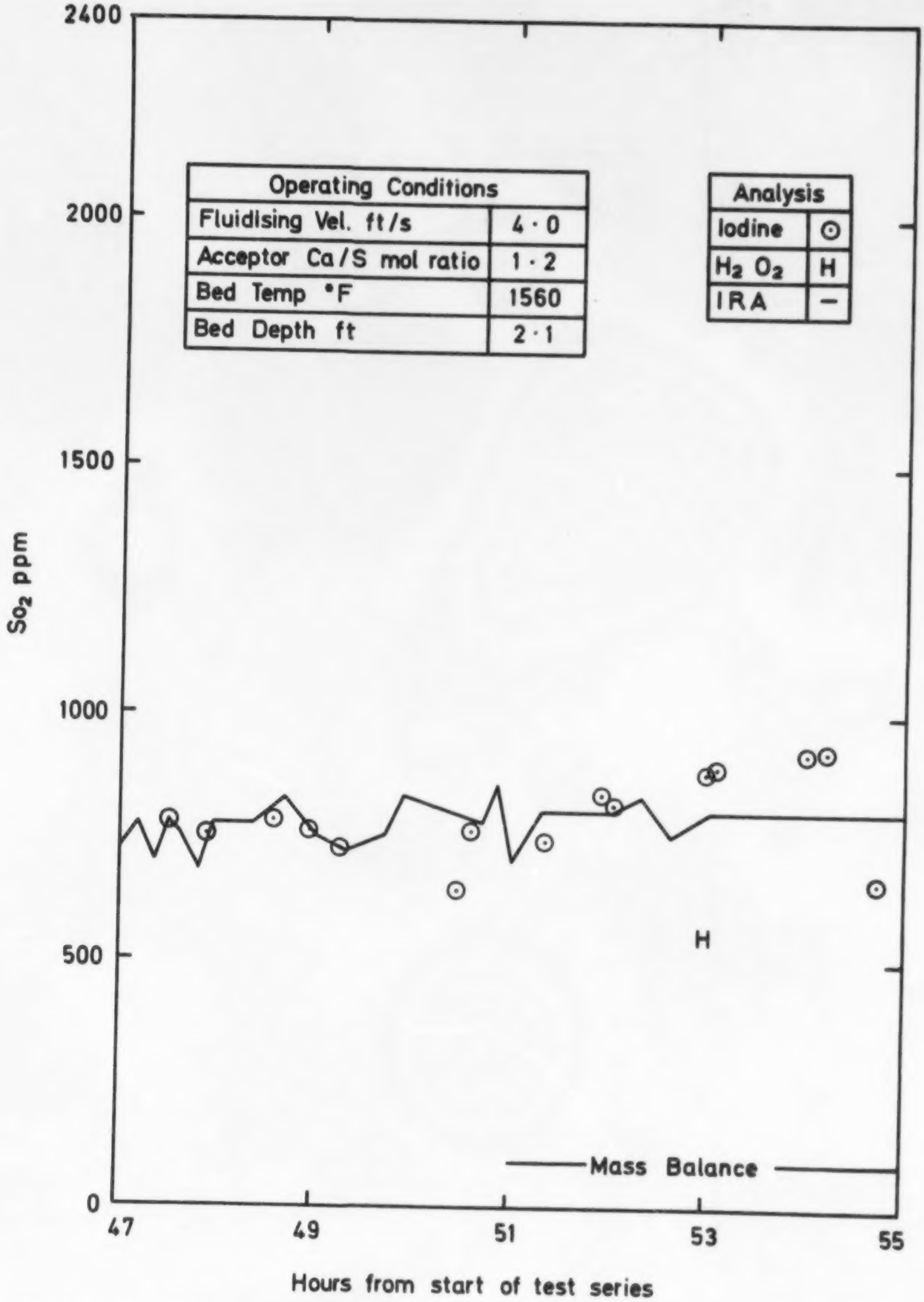


Fig. A1.1.11. SO_2 concentration in Test 1·9

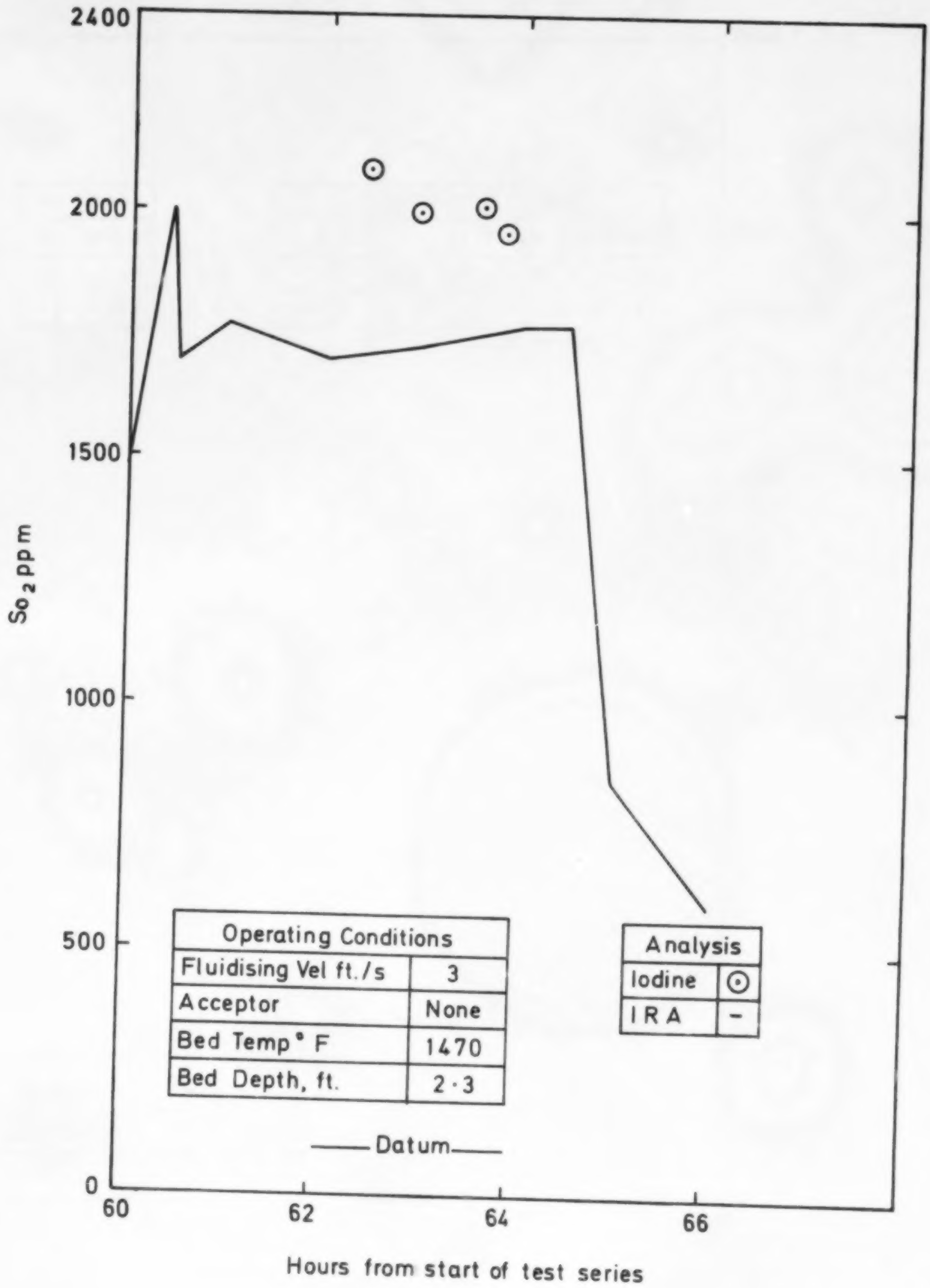


Fig. A.1.1.12. Datum SO_2 concentration for tests 1·10 and 1·11

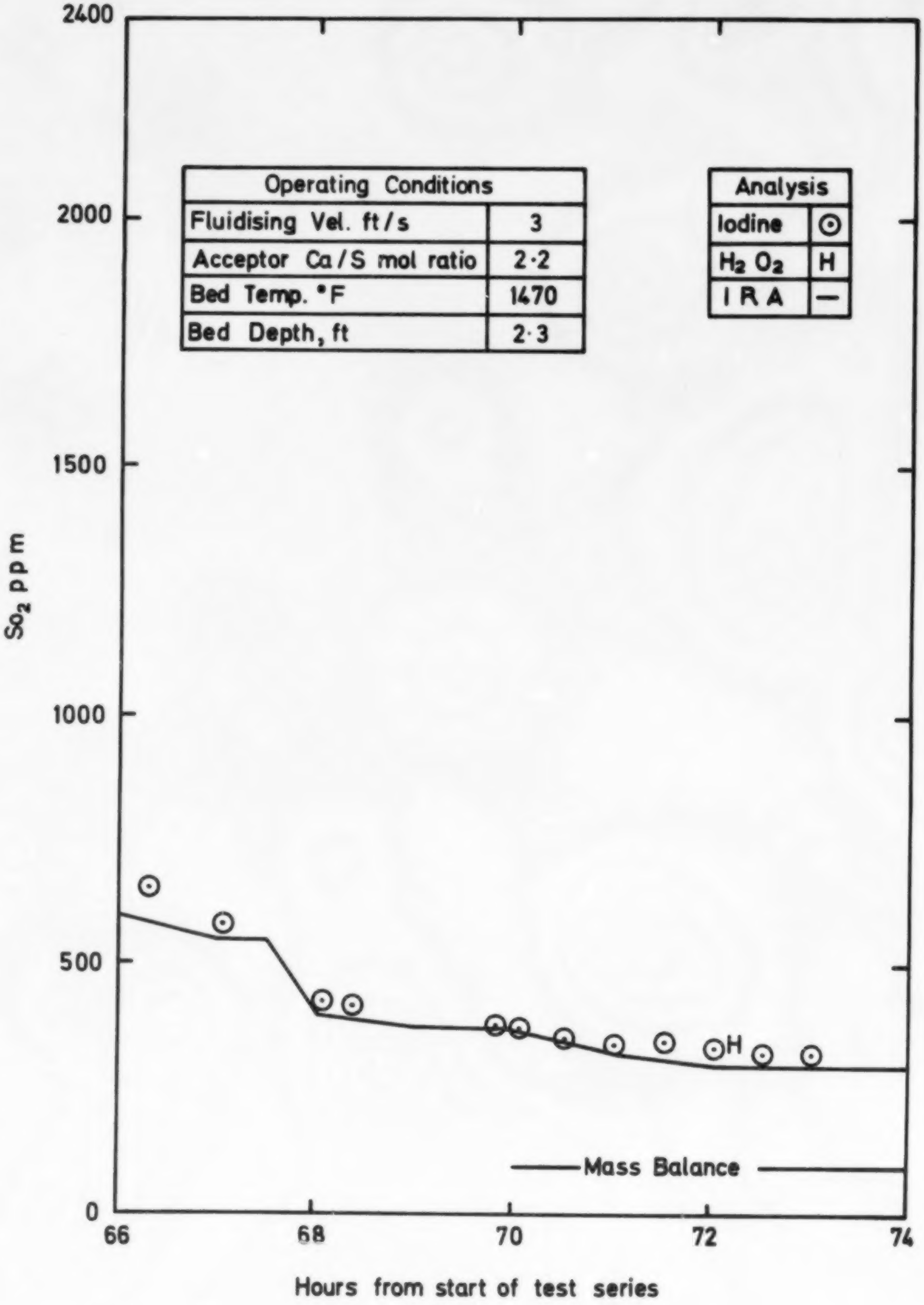


Fig. A 1.1.13. So$_2$ concentrations in Test 1·10

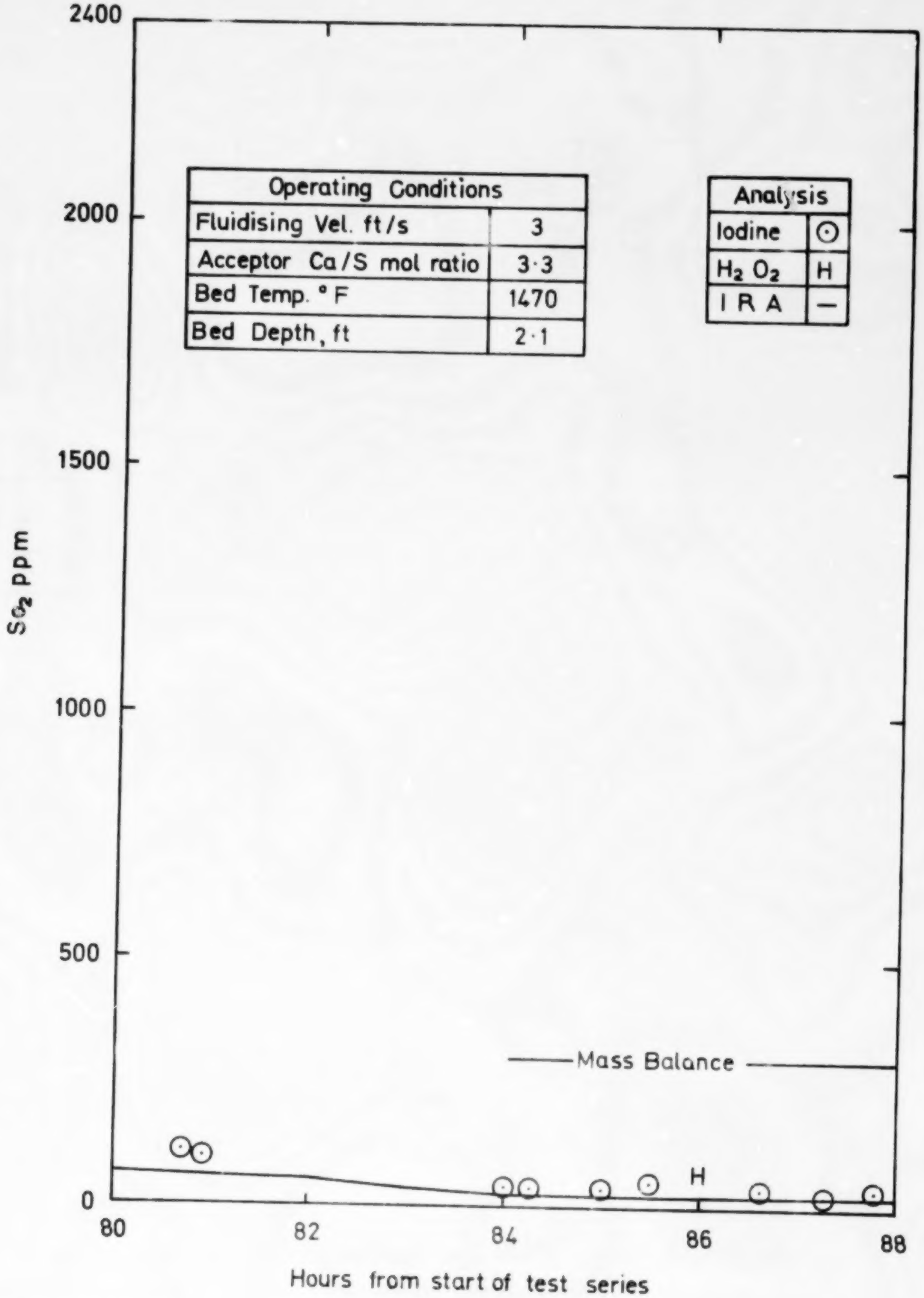
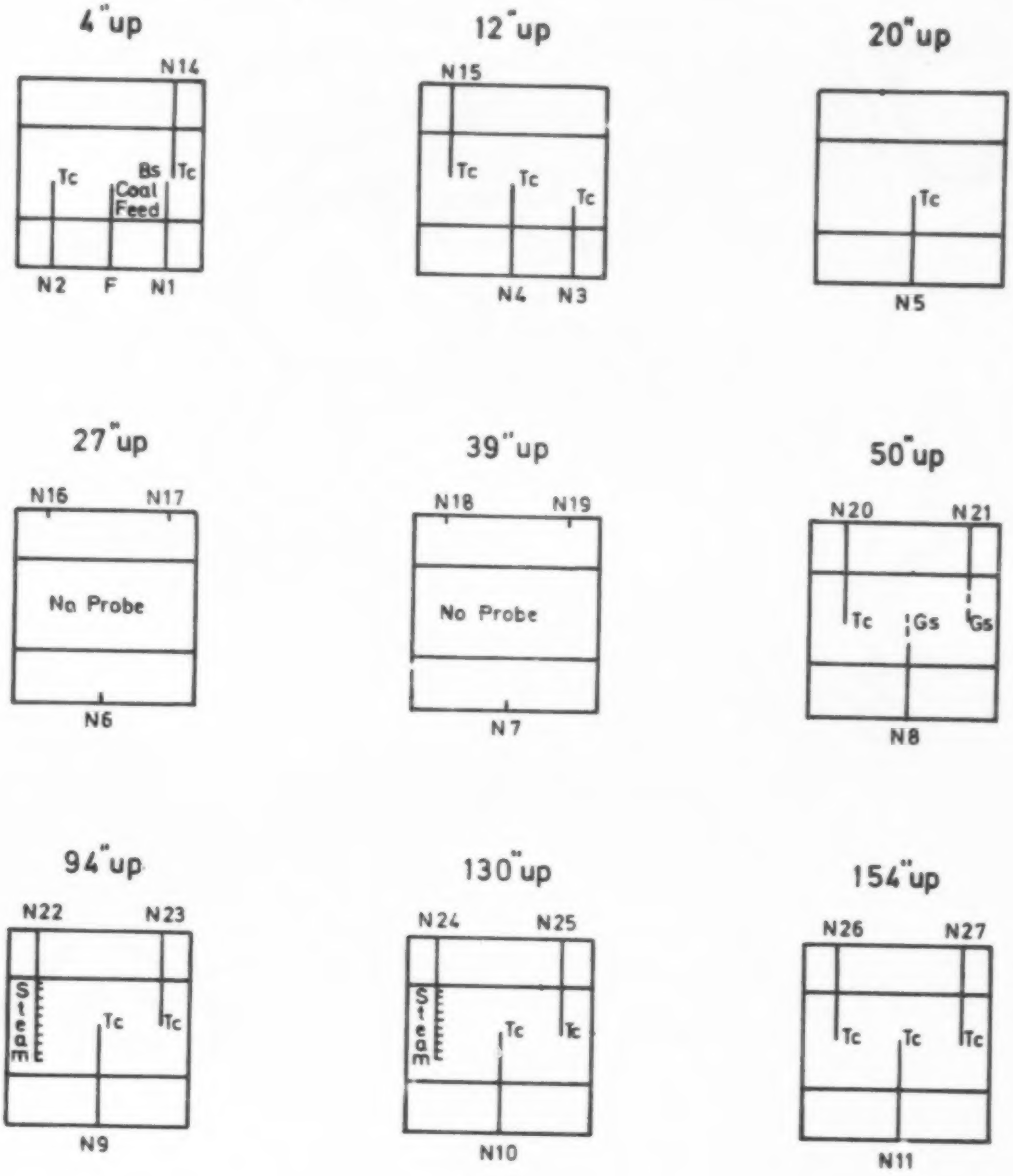
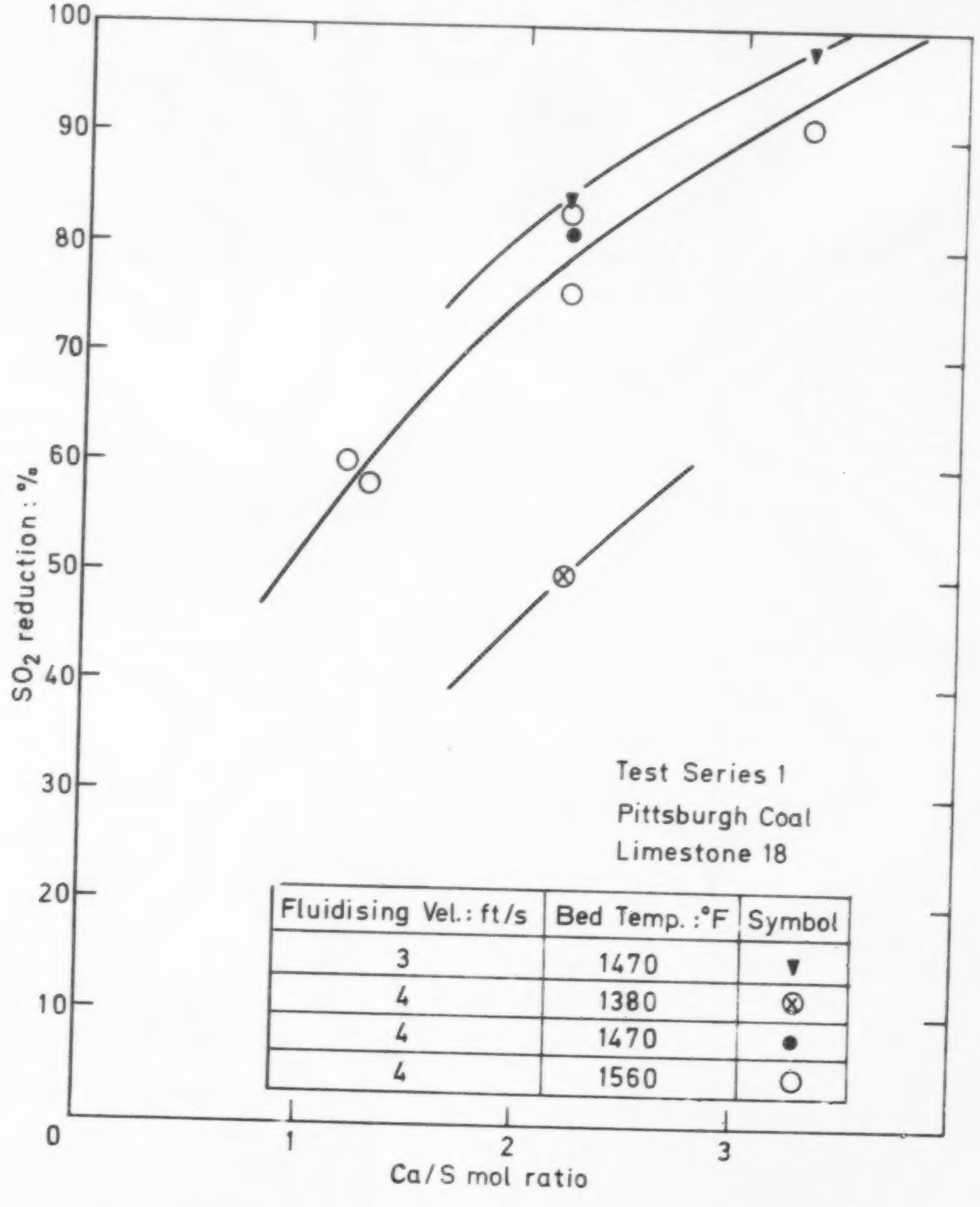


Fig. A1.1.14. So$_2$ concentrations in Test 1·11



Key	
Thermocouple	TC
Bed Ash Sampler	BS
Gas Sampler	GS

Fig. A.1.1.15 Cross-sections of 36in combustor at varying heights above air jets showing typical positions of thermocouples in Test Series 1



Fluidising Vel.: ft/s	Bed Temp. :°F	Symbol
3	1470	▼
4	1380	⊗
4	1470	●
4	1560	○

Fig. A1.1.16. SO_2 reduction in Test Series 1

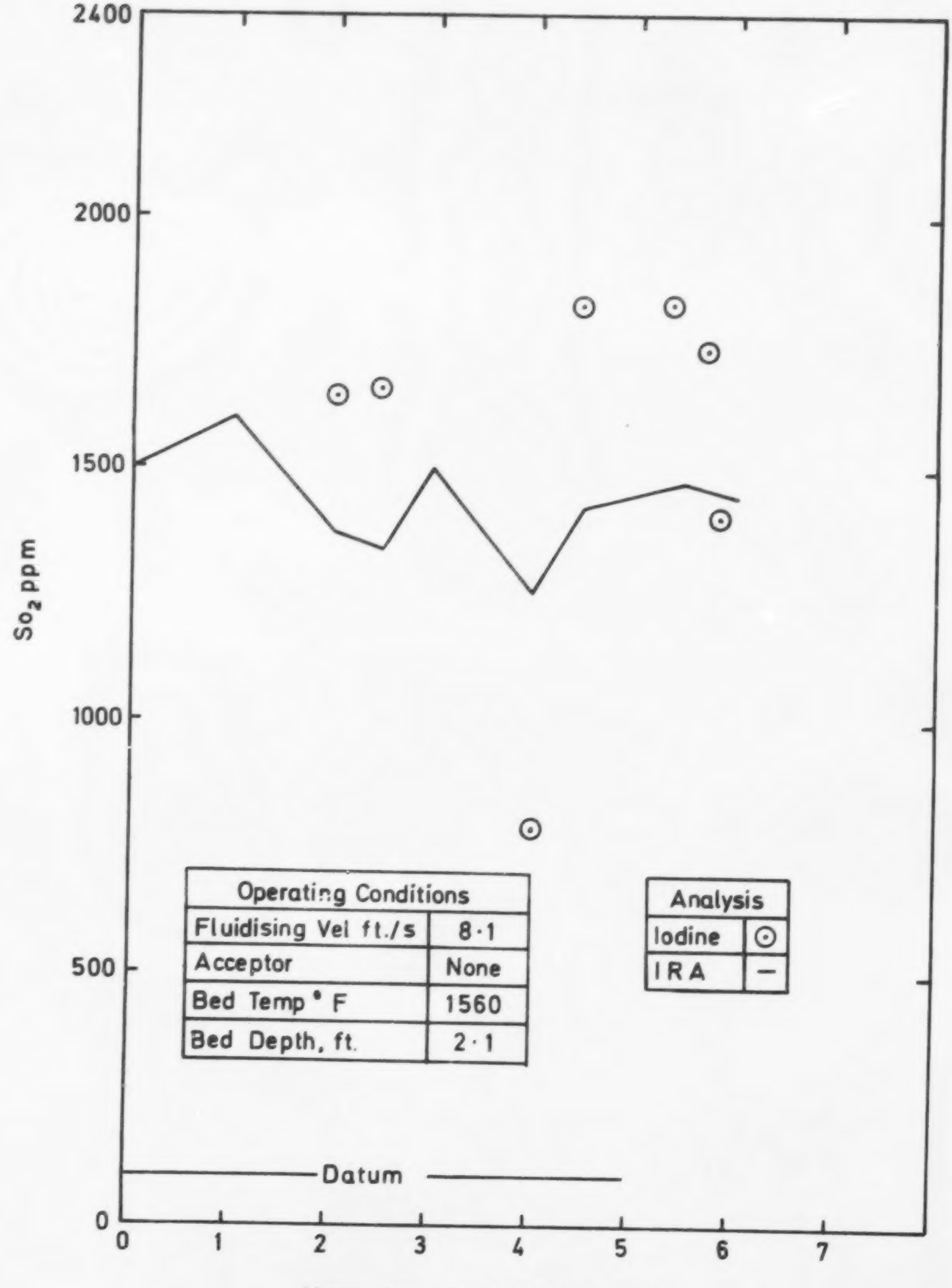


Fig. A.1.2.1. Datum So$_2$ concentration for tests 2·1 to 2·3

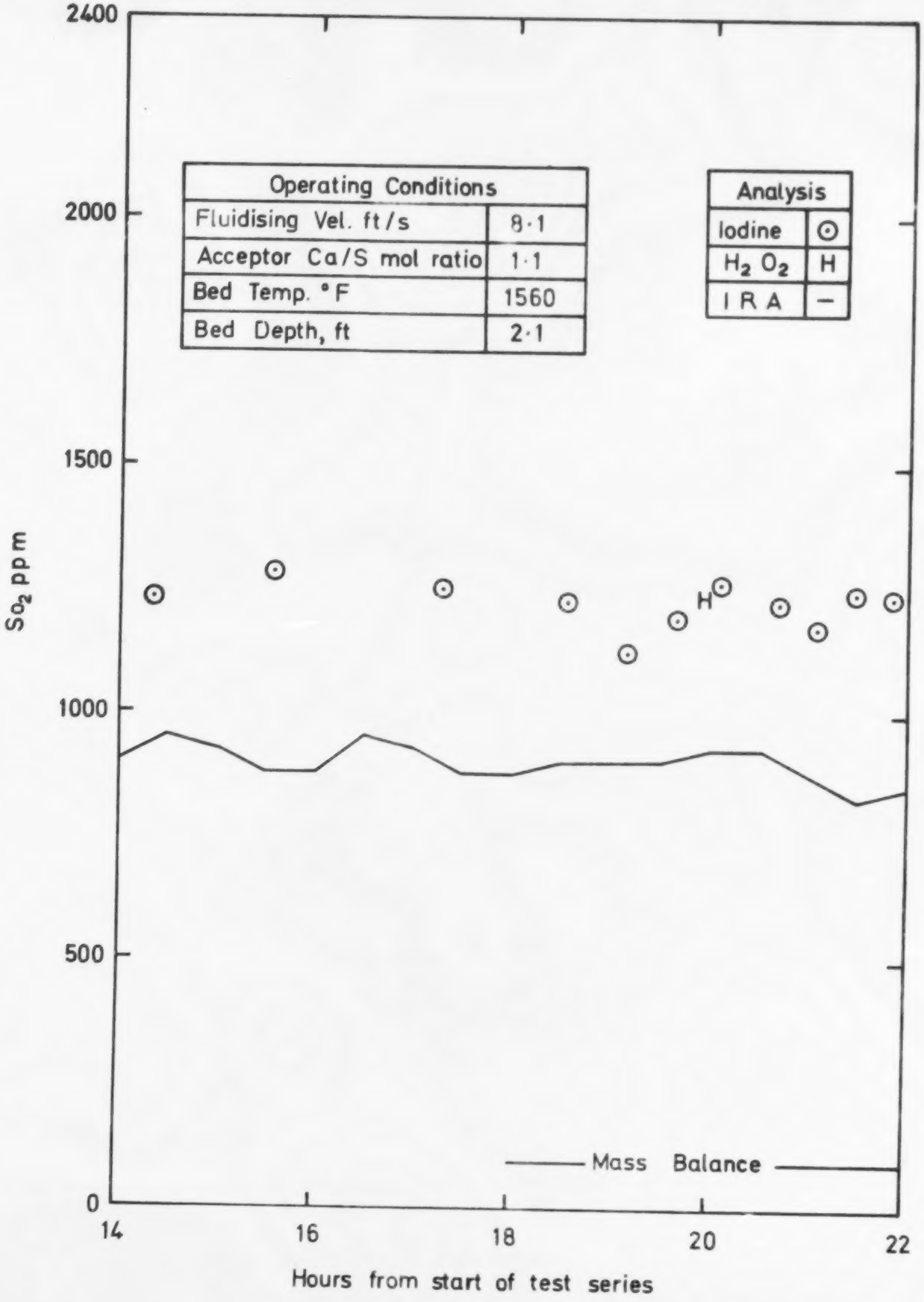
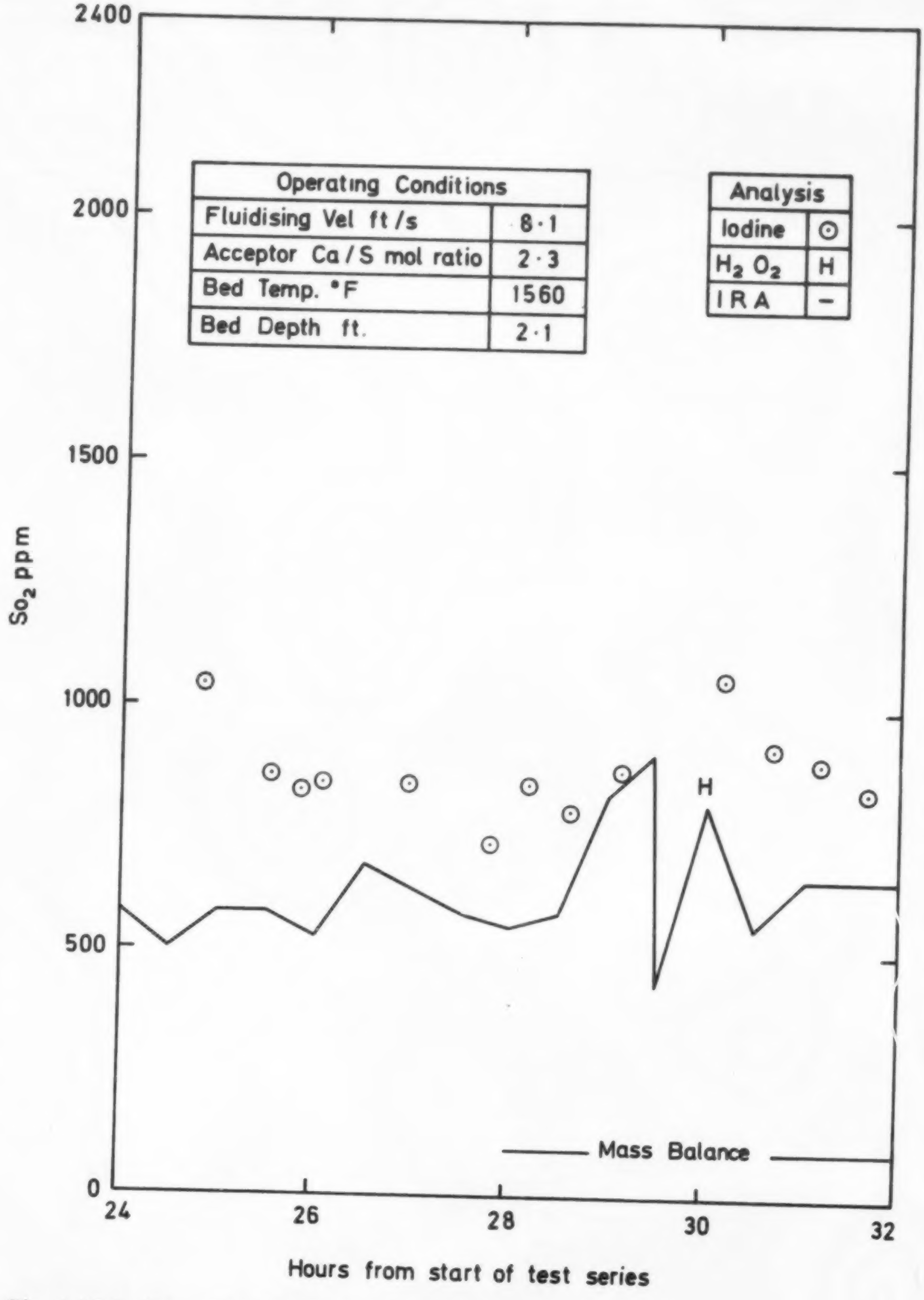


Fig. A 1.2.2. So$_2$ concentrations in Test 2·1



Operating Conditions	
Fluidising Vel ft/s	8·1
Acceptor Ca/S mol ratio	2·3
Bed Temp. °F	1560
Bed Depth ft.	2·1

Analysis	
Iodine	⊙
H_2O_2	H
IRA	–

Fig. A.1.2.3. SO_2 concentrations in Test 2·2

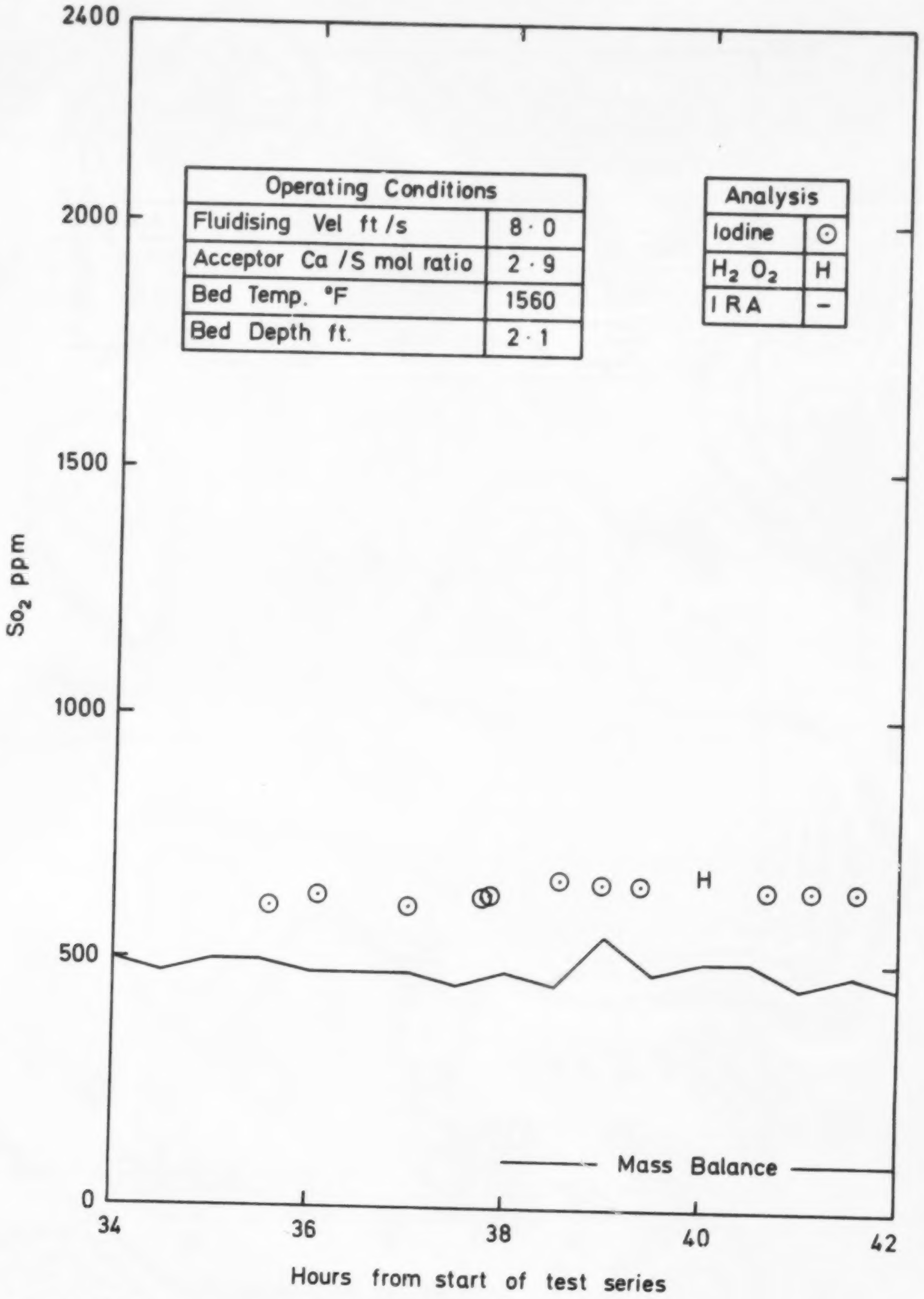


Fig. A 1.2.4. SO_2 concentrations in Test 2·3

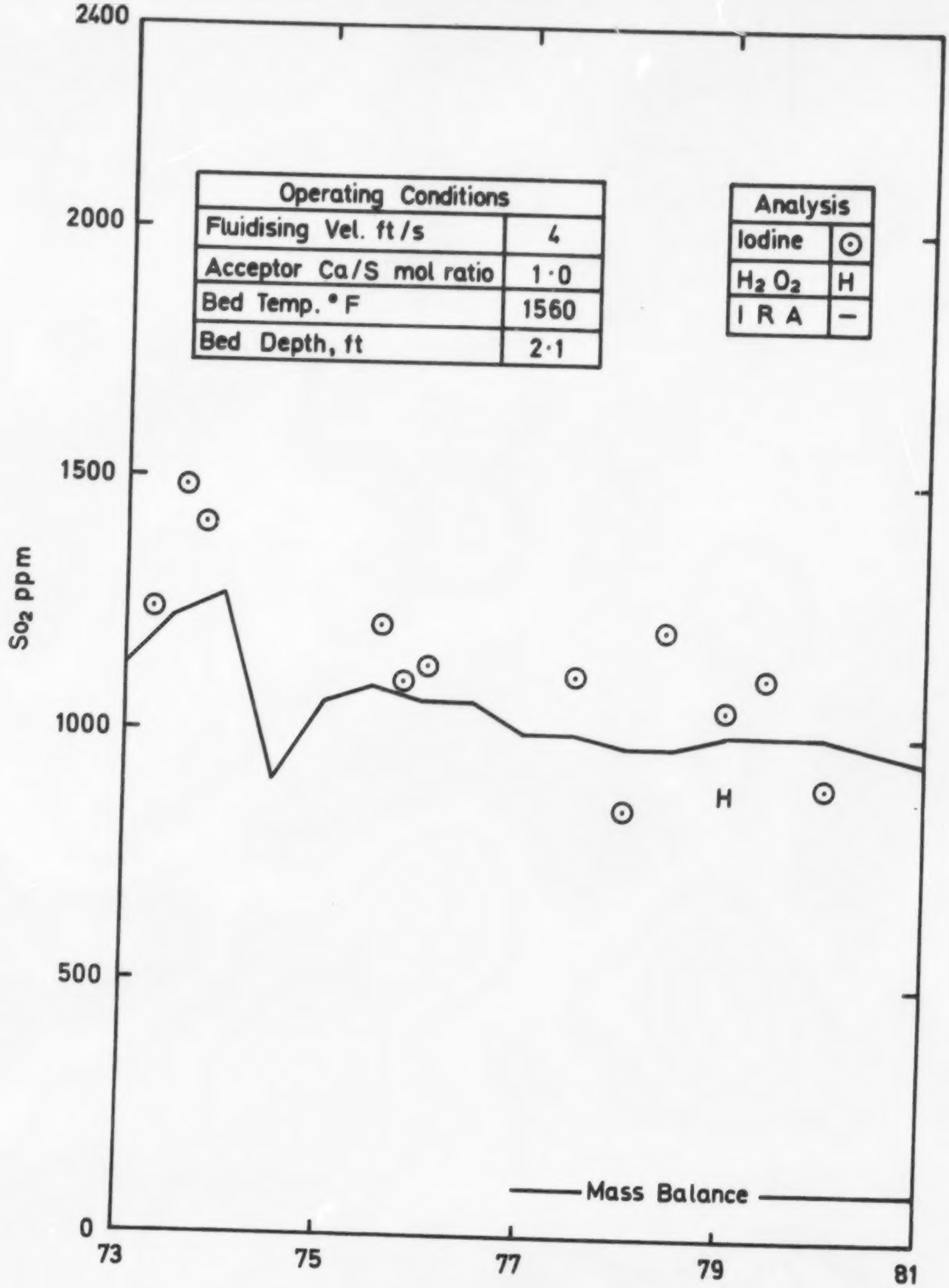


Fig. A1.2.5. SO_2 concentrations in Test 2·4

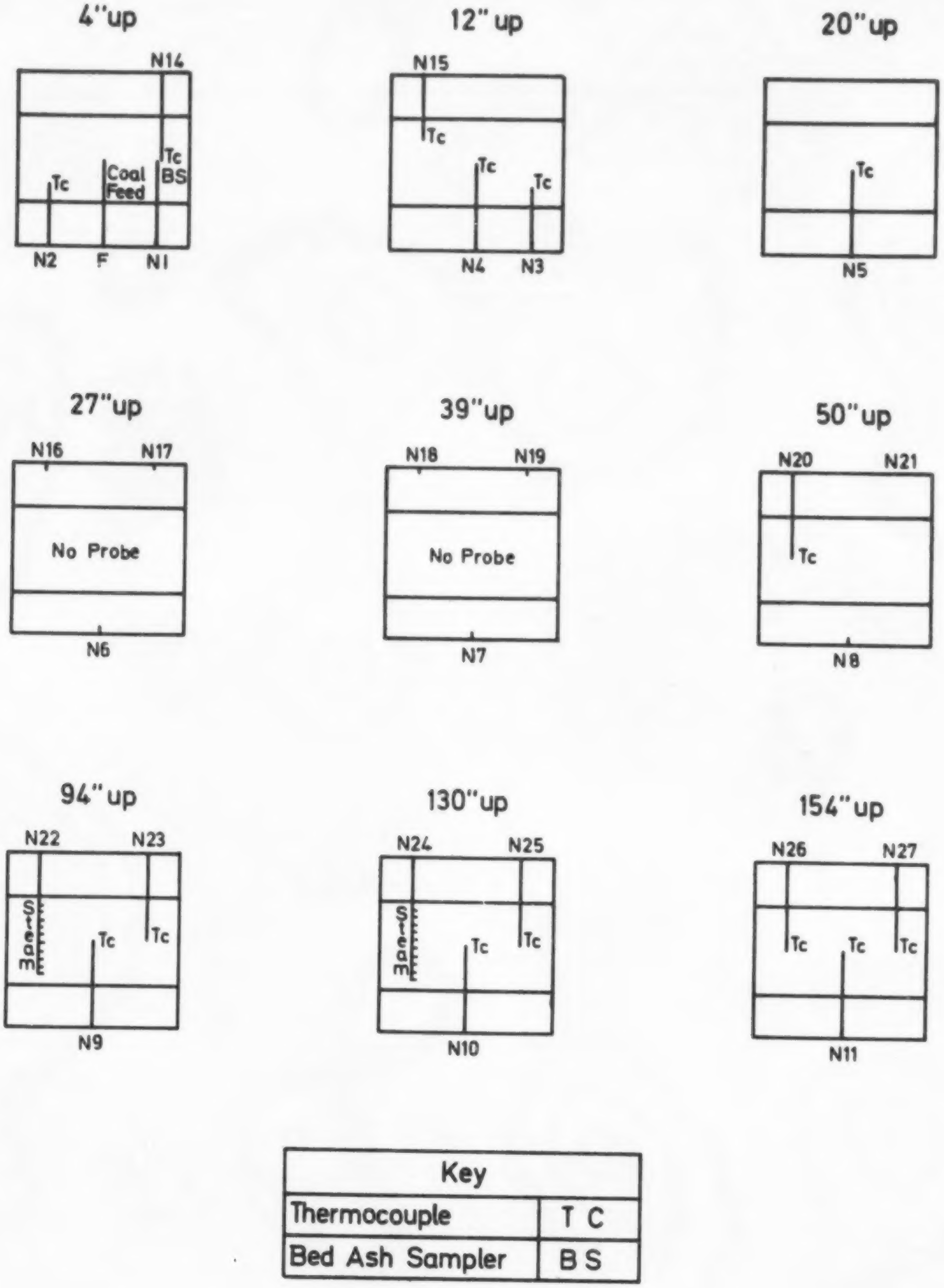
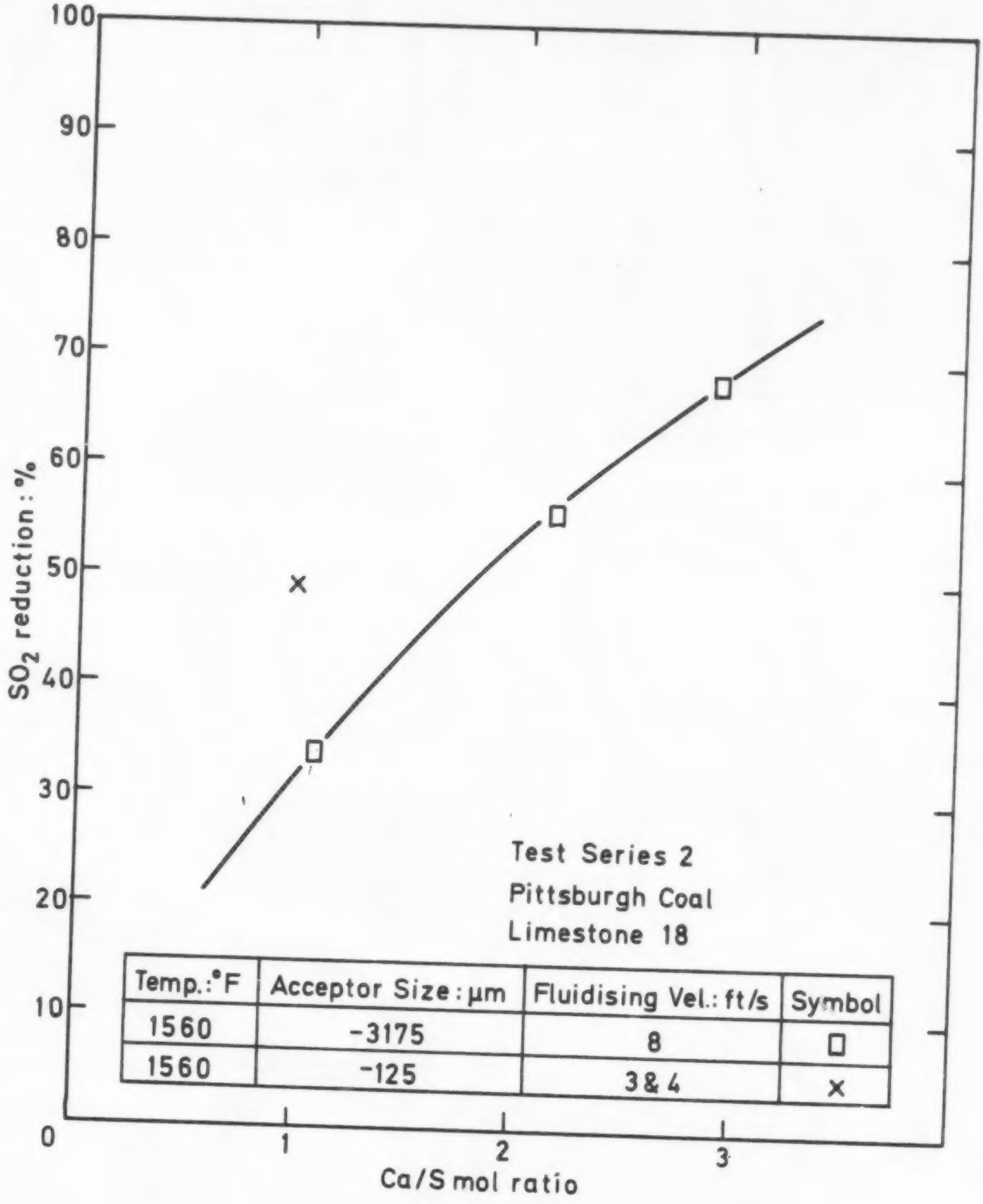


Fig. A.1.2.6. Cross-sections of 36 in combustor at varying heights above air jets showing positions of thermocouples in Test Series 2



Temp.:°F	Acceptor Size : μm	Fluidising Vel.: ft/s	Symbol
1560	-3175	8	□
1560	-125	3& 4	×

Fig. A1. 2.7. SO_2 reduction in Test Series 2

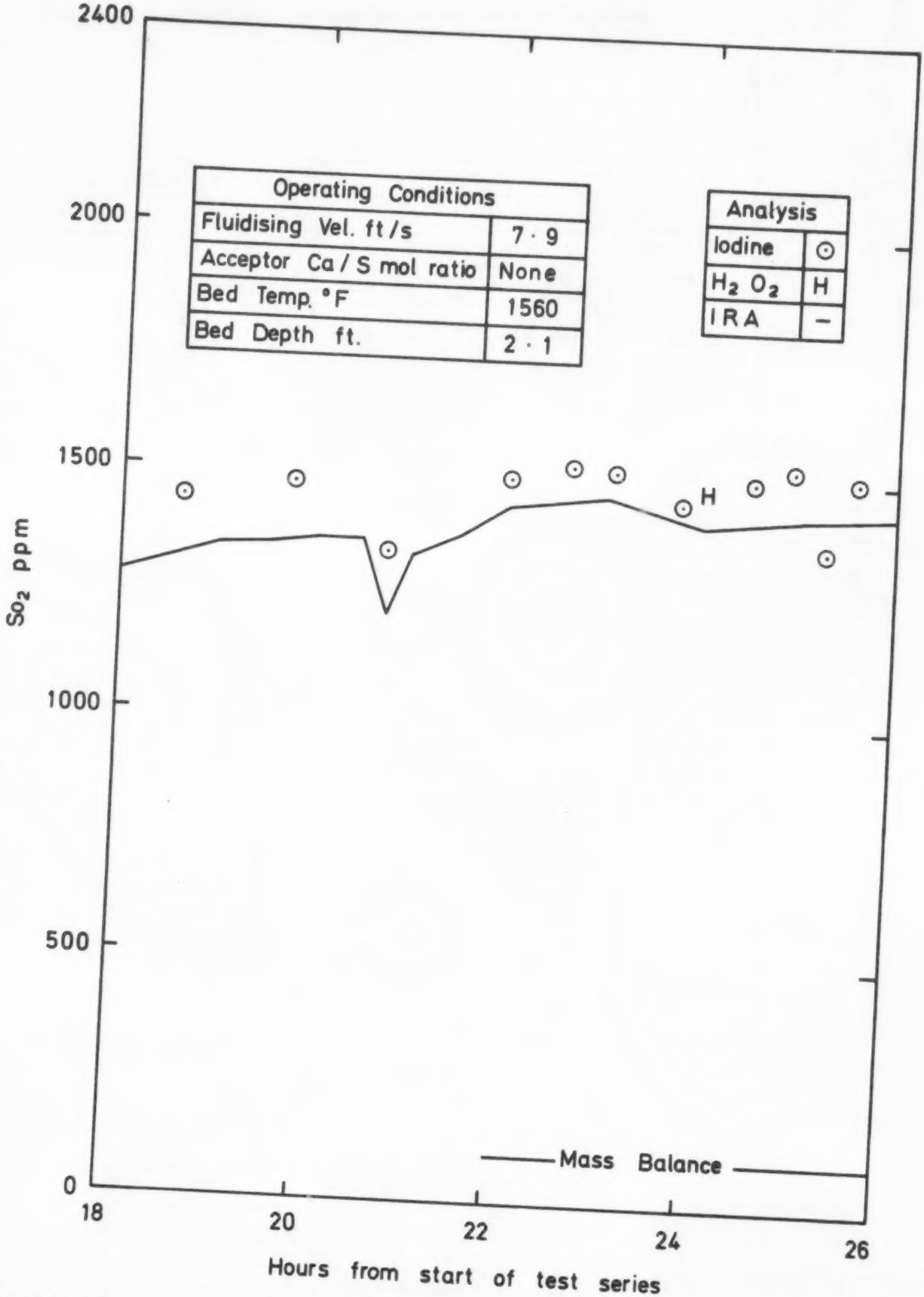


Fig. A 1.3.1. SO_2 concentrations in Test 3·1

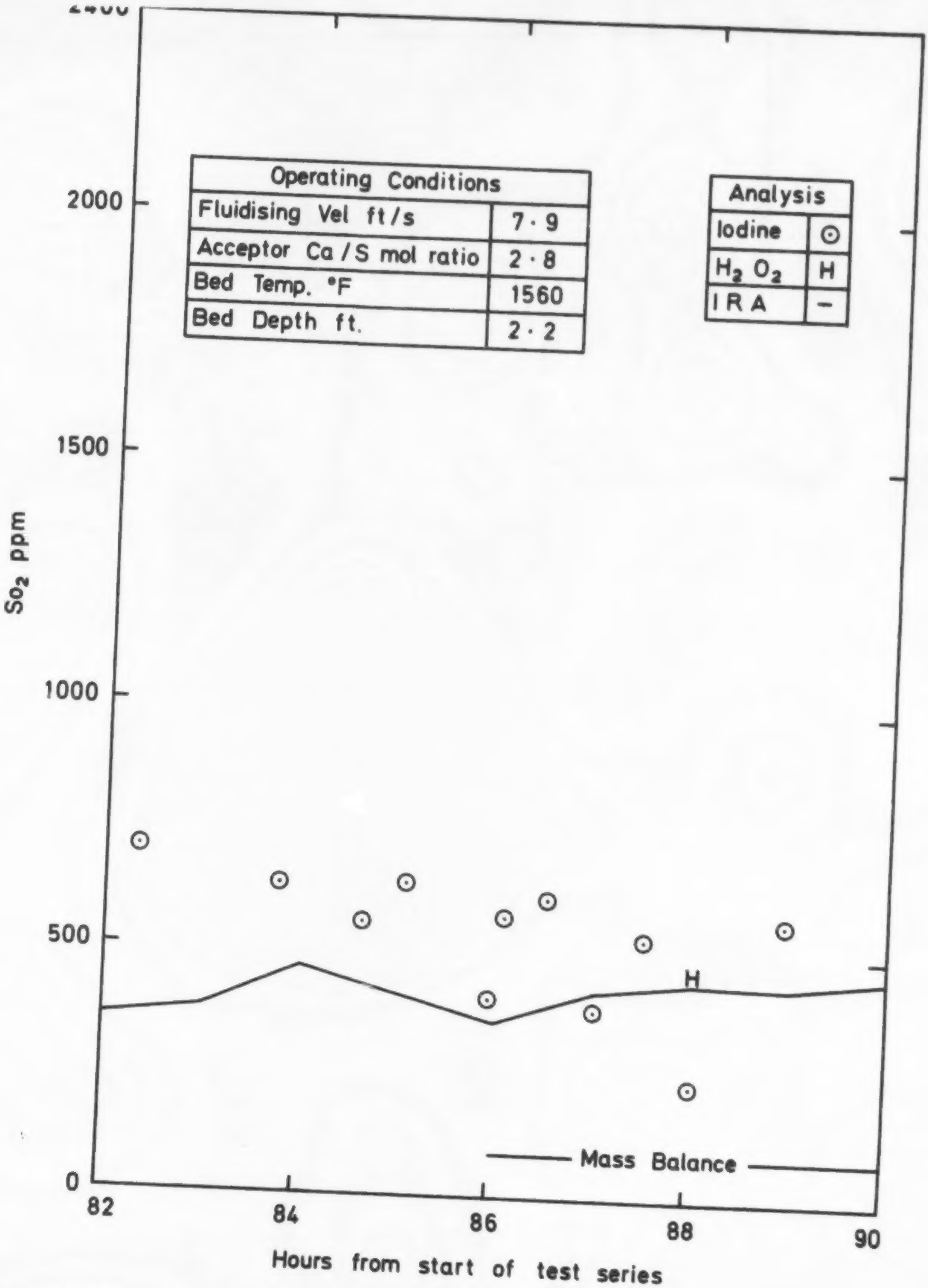


Fig. A.1.3.4. So$_2$ concentrations in Test 3·4

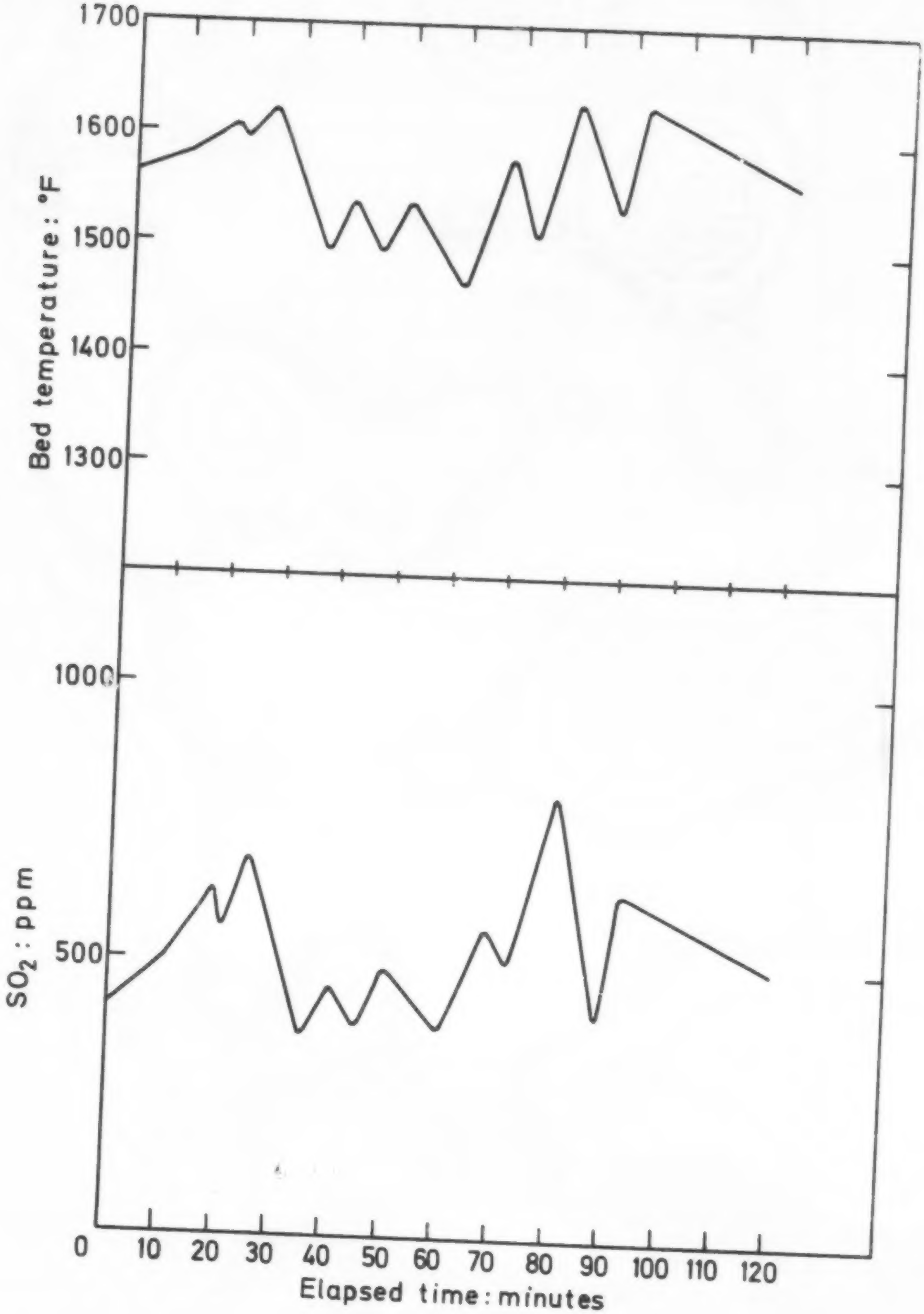


Fig. A1. 3.5. SO_2 concentrations during the bed temperature survey (Ca/S mol ratio 2·8 : 8ft/s : 2·2ft bed)

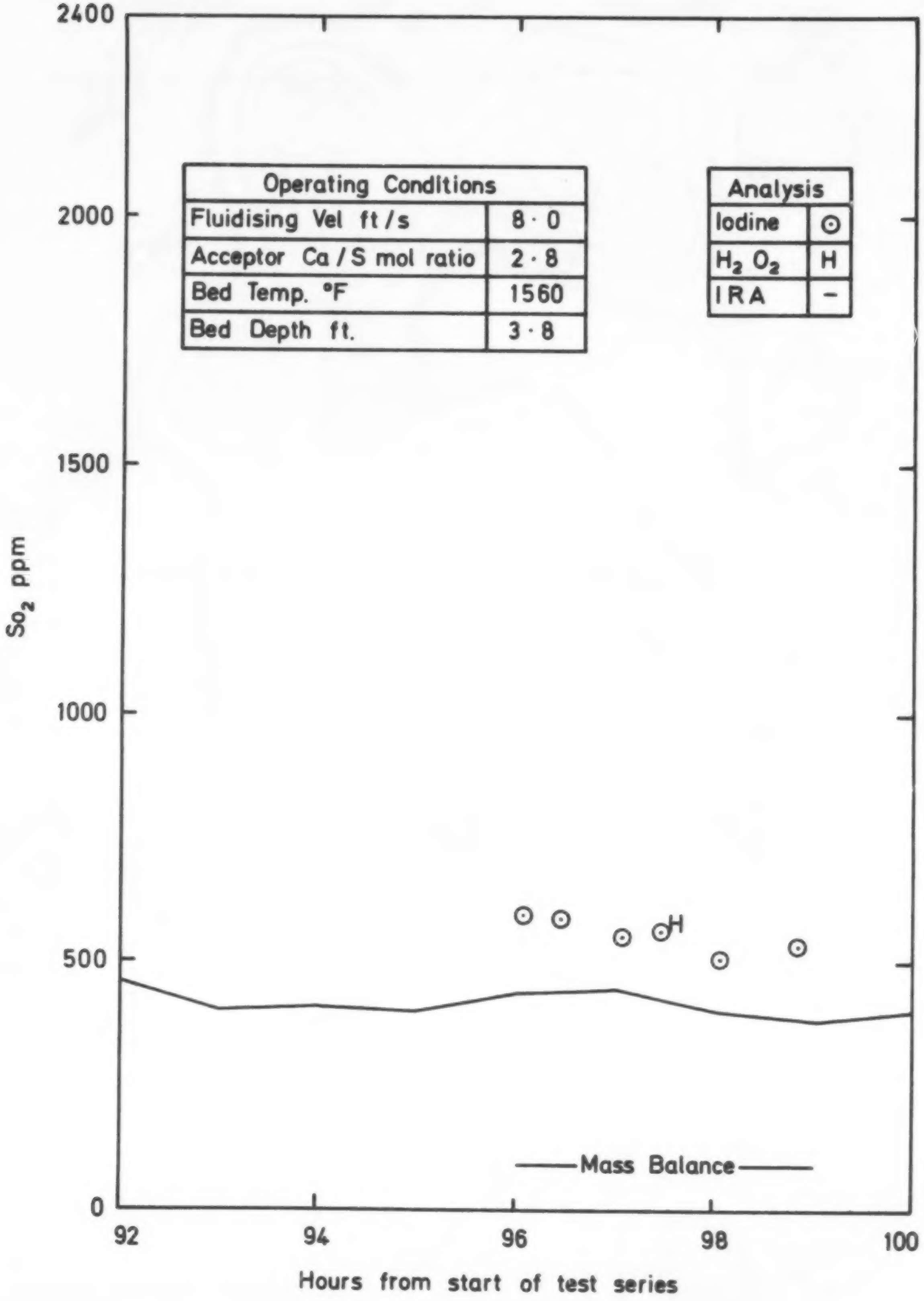


Fig. A 1.3.6. SO_2 concentrations in Test 3·5

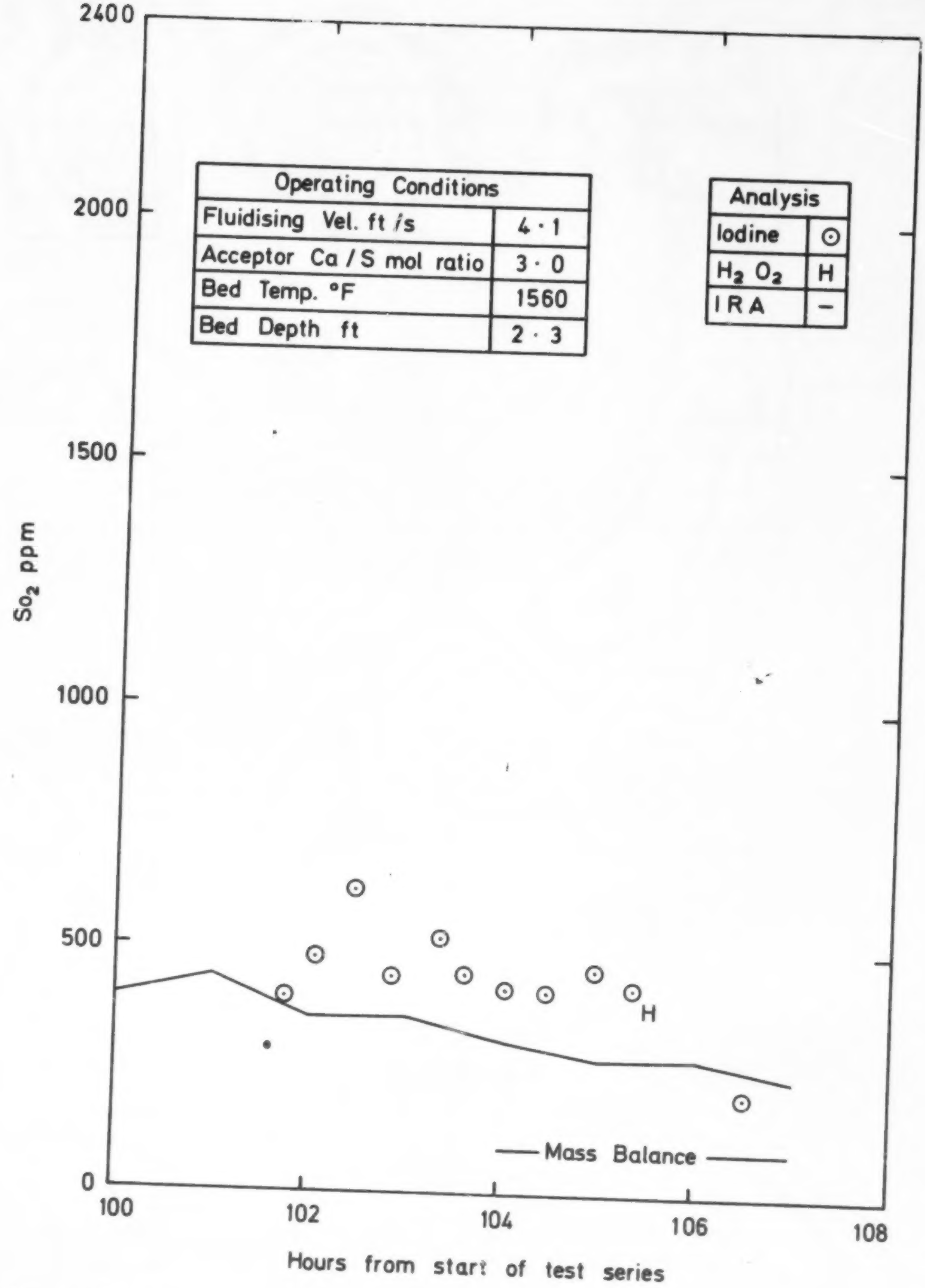
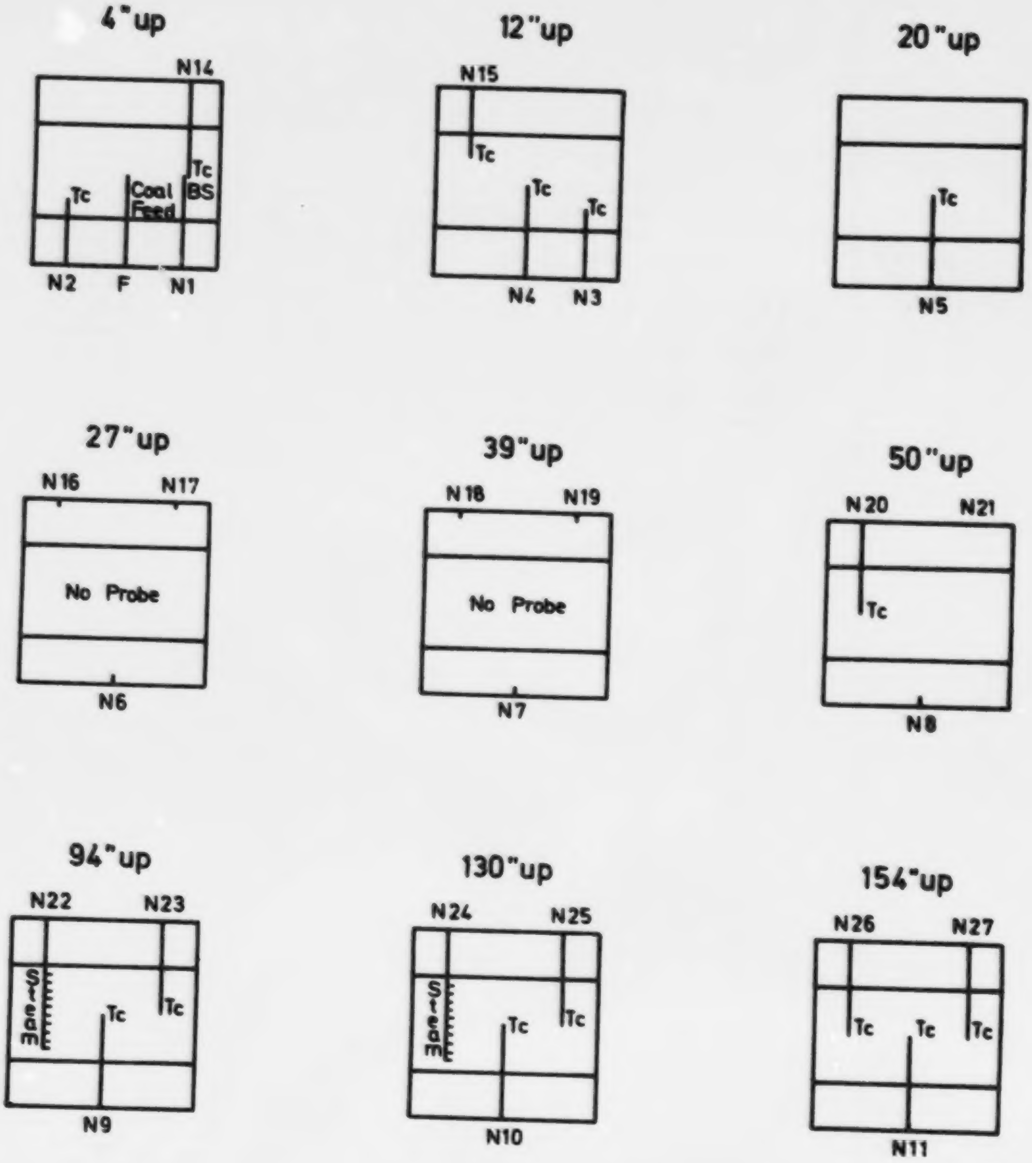


Fig. A.1.3.7. So$_2$ concentrations in Test 3·6



Key	
Thermocouple	T C
Bed Ash Sampler	B S

Fig. A.1.3.8. Cross-sections of 36in combustor at varying heights above air jets showing positions of thermocouples in Test Series 3

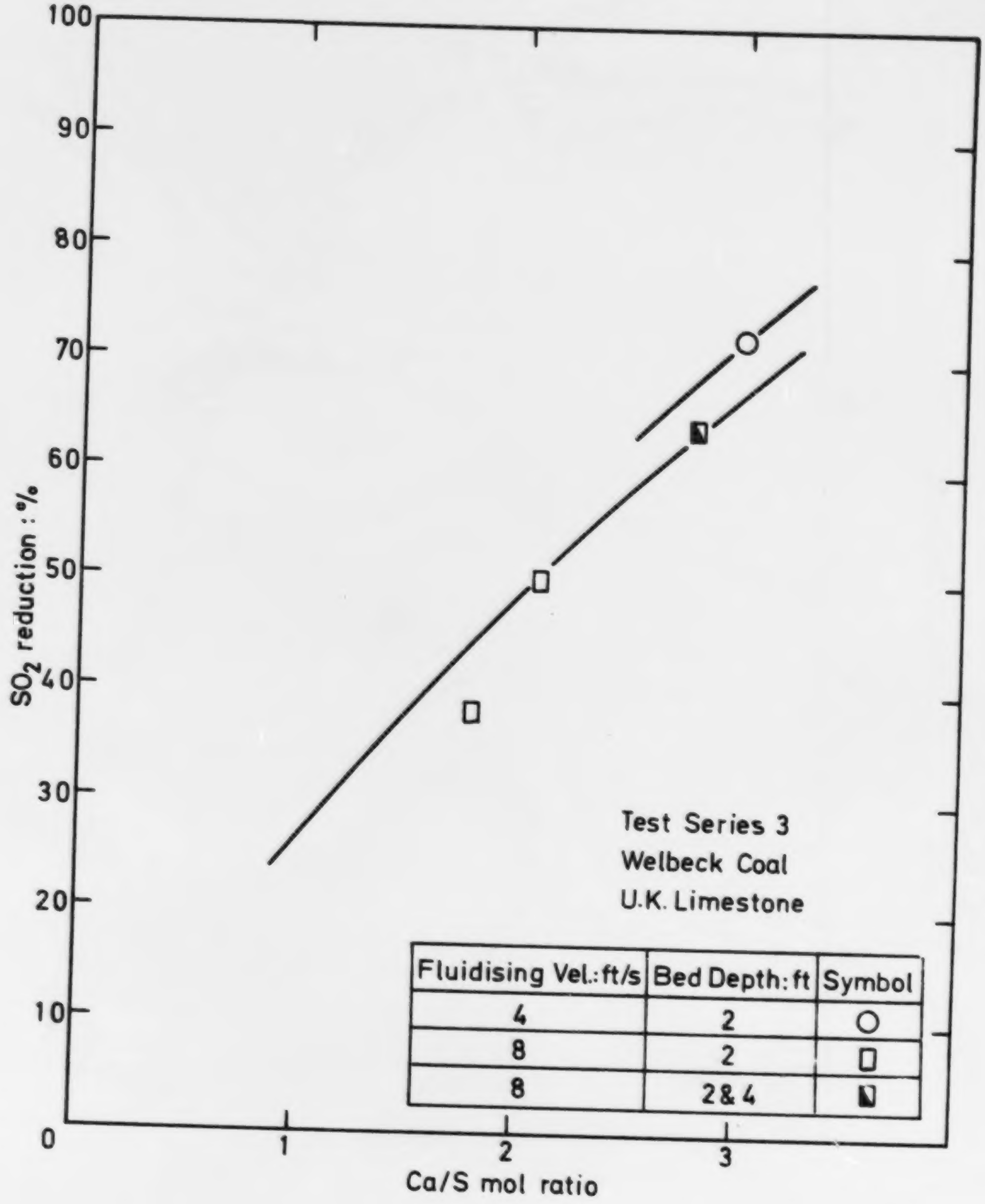


Fig. A1. 3.9. SO_2 reduction in Test Series 3

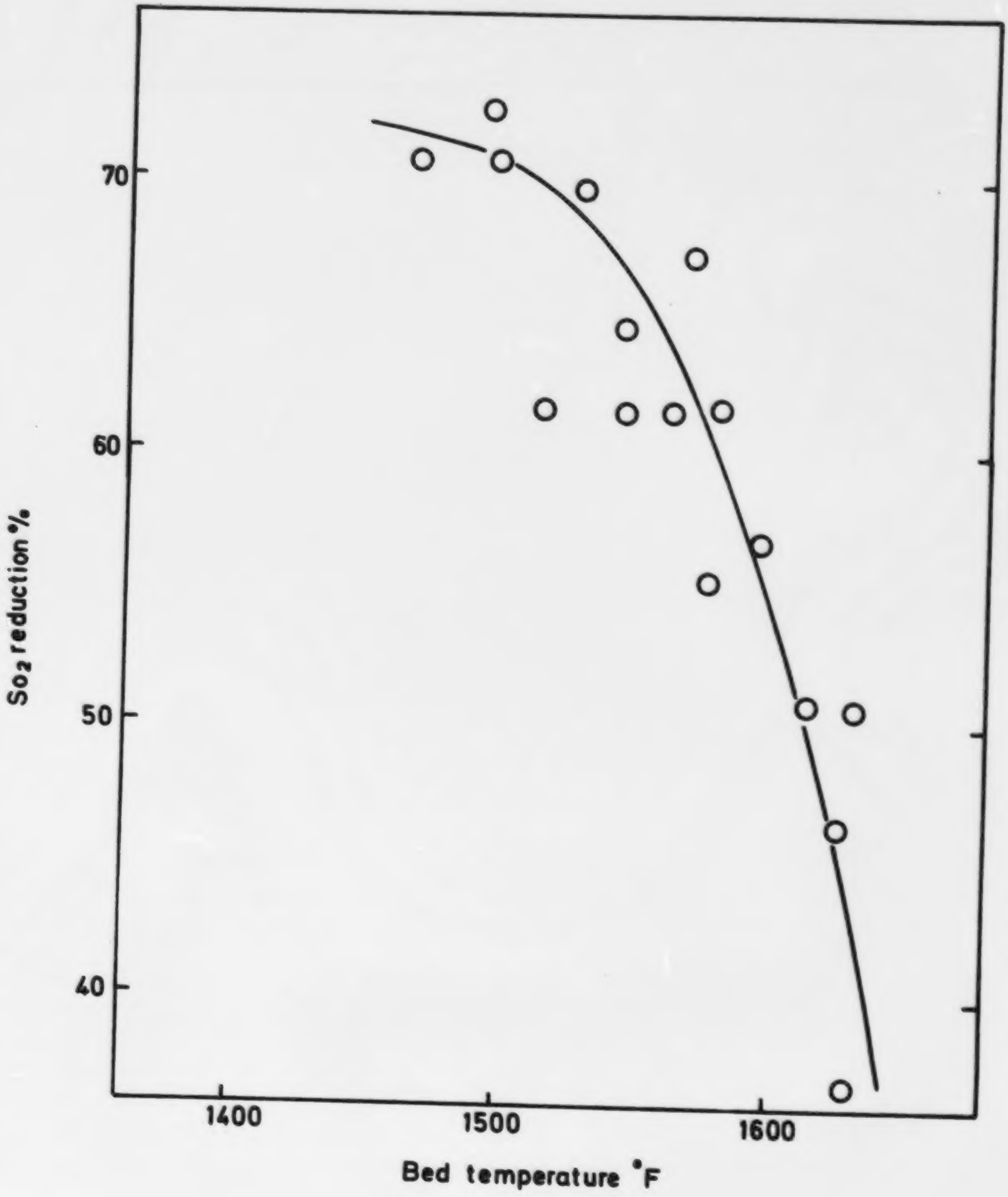
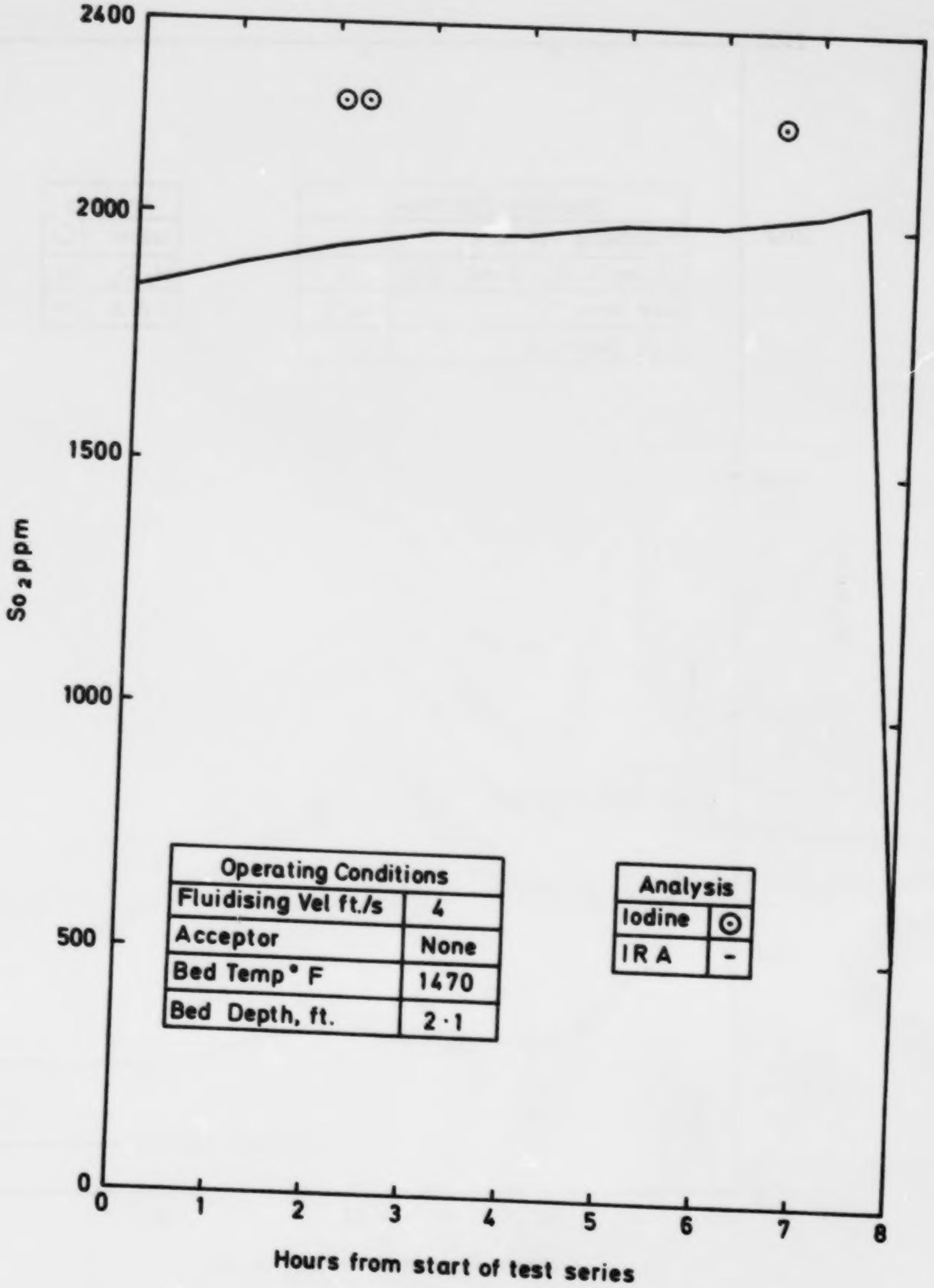


Fig A.1.3.10. SO_2 reduction during the bed temperature survey



Operating Conditions	
Fluidising Vel ft./s	4
Acceptor	None
Bed Temp° F	1470
Bed Depth, ft.	2·1

Analysis	
Iodine	⊙
IR A	-

Fig A.1.4.1. Datum SO_2 concentration for test series 4

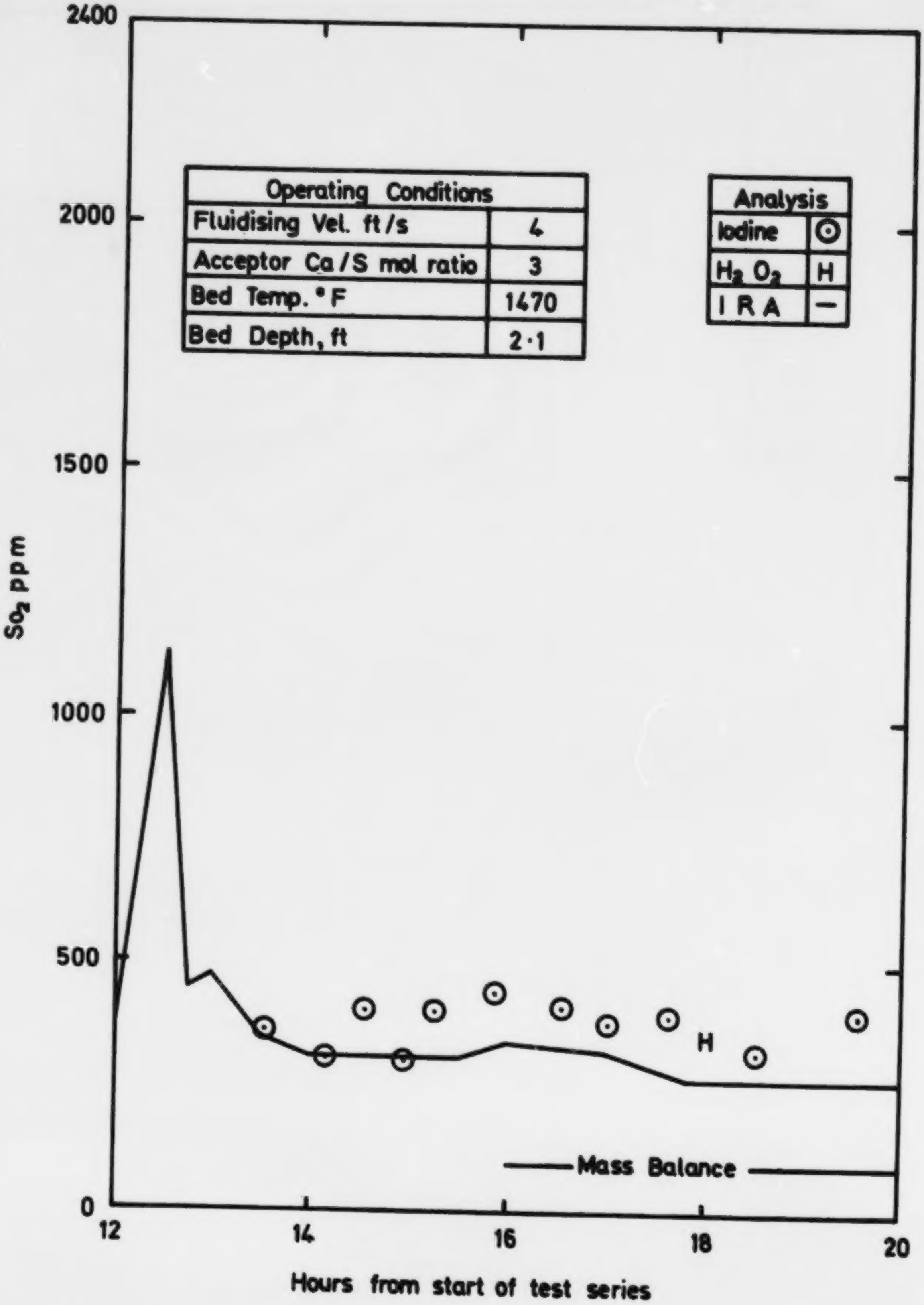


Fig A1.4.2. So$_2$ concentrations in Test 4·1

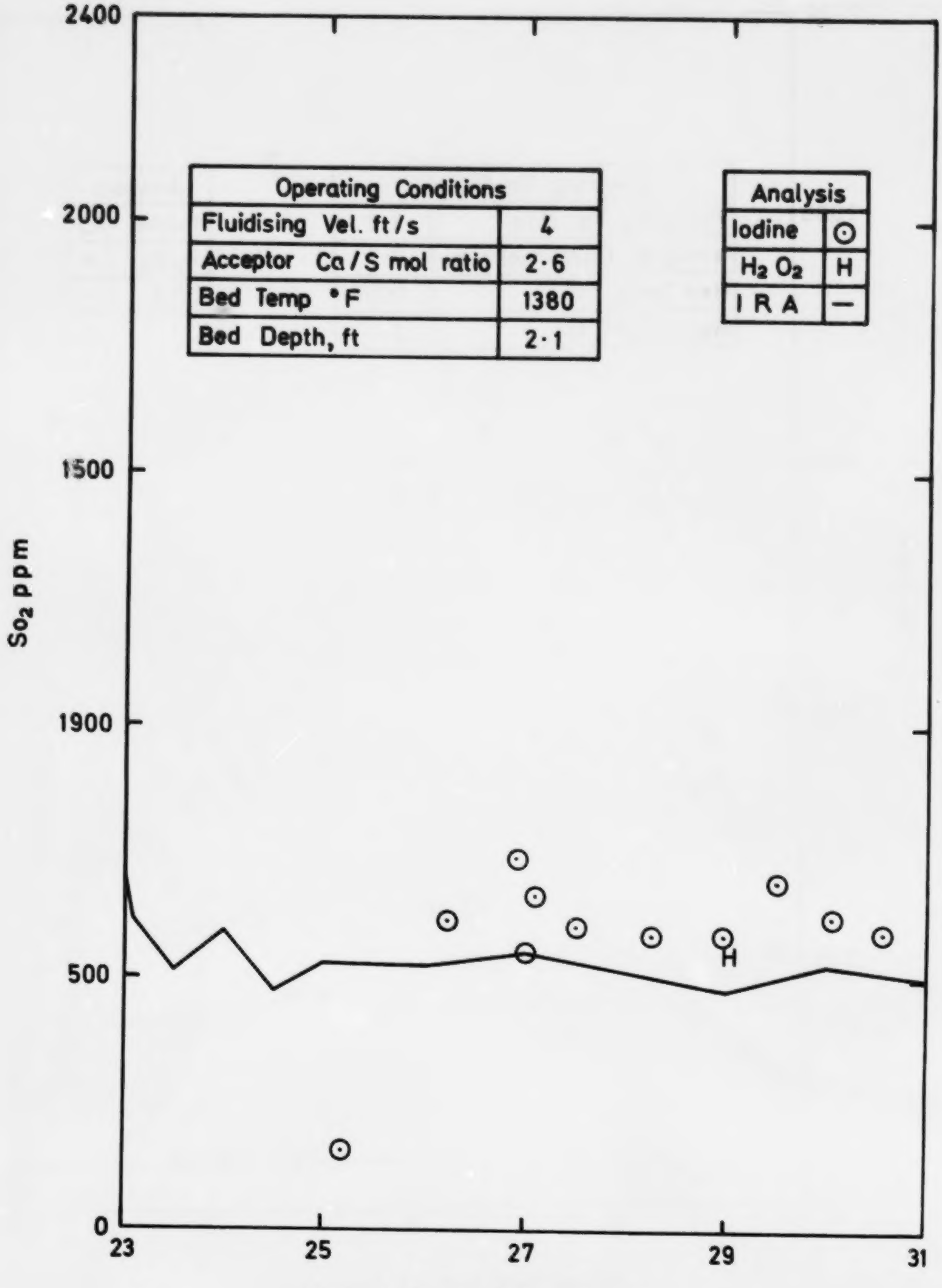
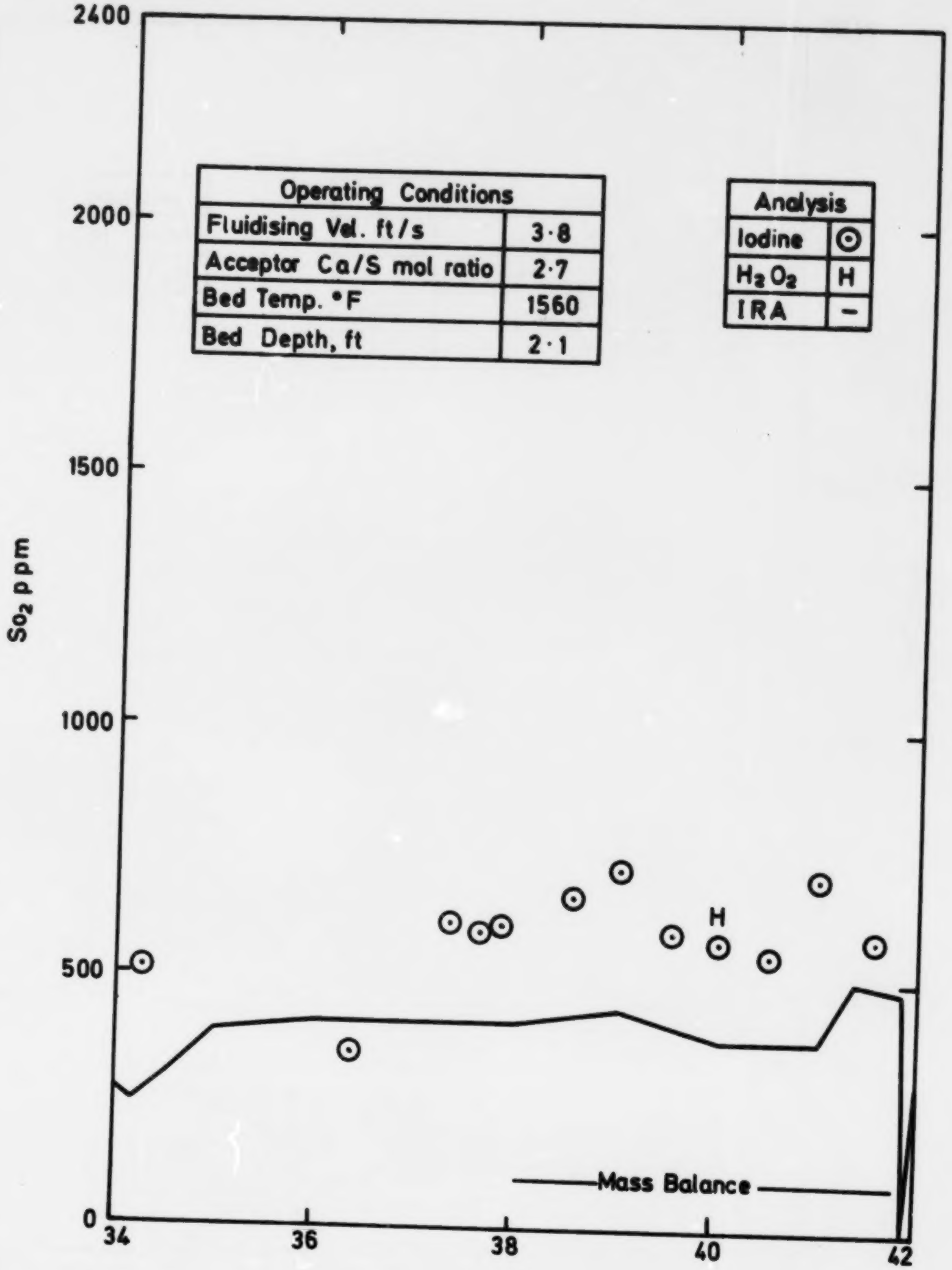


Fig. A 1.4.3. SO_2 concentrations in Test 4·2



Operating Conditions	
Fluidising Vel. ft/s	3·8
Acceptor Ca/S mol ratio	2·7
Bed Temp. °F	1560
Bed Depth, ft	2·1

Fig. A.1.4.4. SO_2 concentrations in Test 4·3

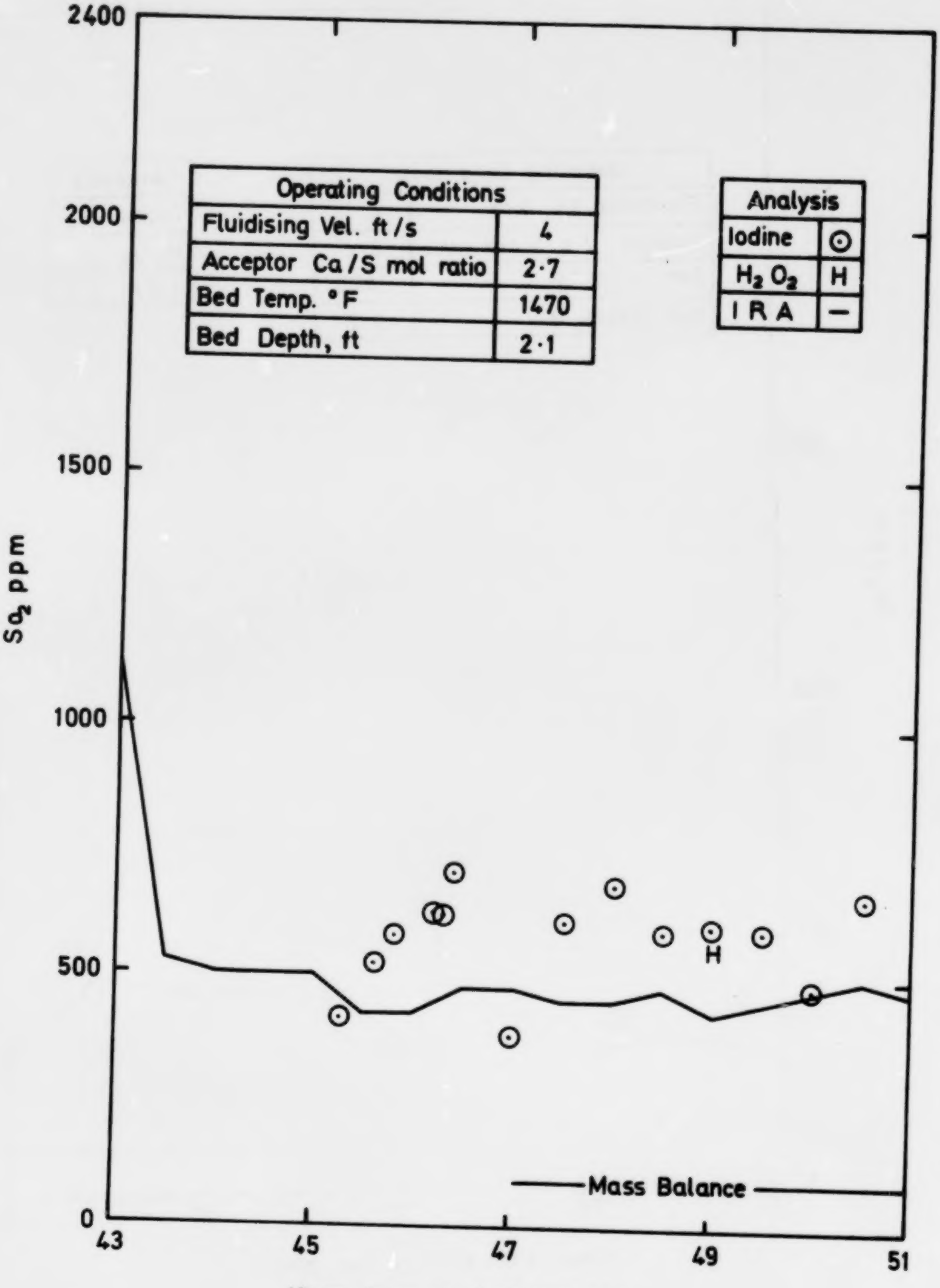
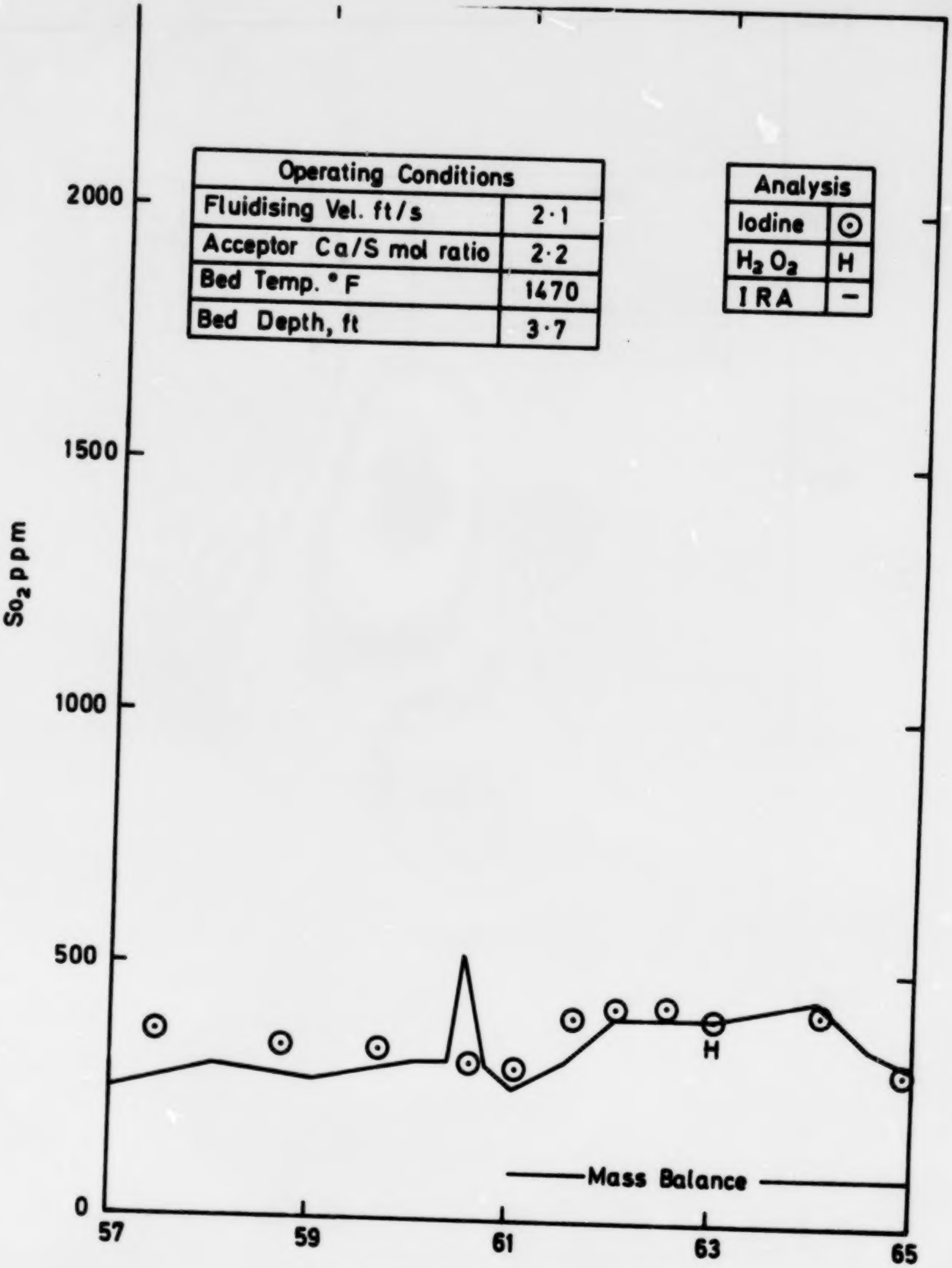


Fig. A 1.4.5. SO_2 concentrations in Test 4·4



Operating Conditions	
Fluidising Vel. ft/s	2·1
Acceptor Ca/S mol ratio	2·2
Bed Temp. °F	1470
Bed Depth, ft	3·7

Analysis	
Iodine	⊙
H_2O_2	H
IRA	–

Fig. A 1.4.6 So$_2$ concentrations in Test 4·5

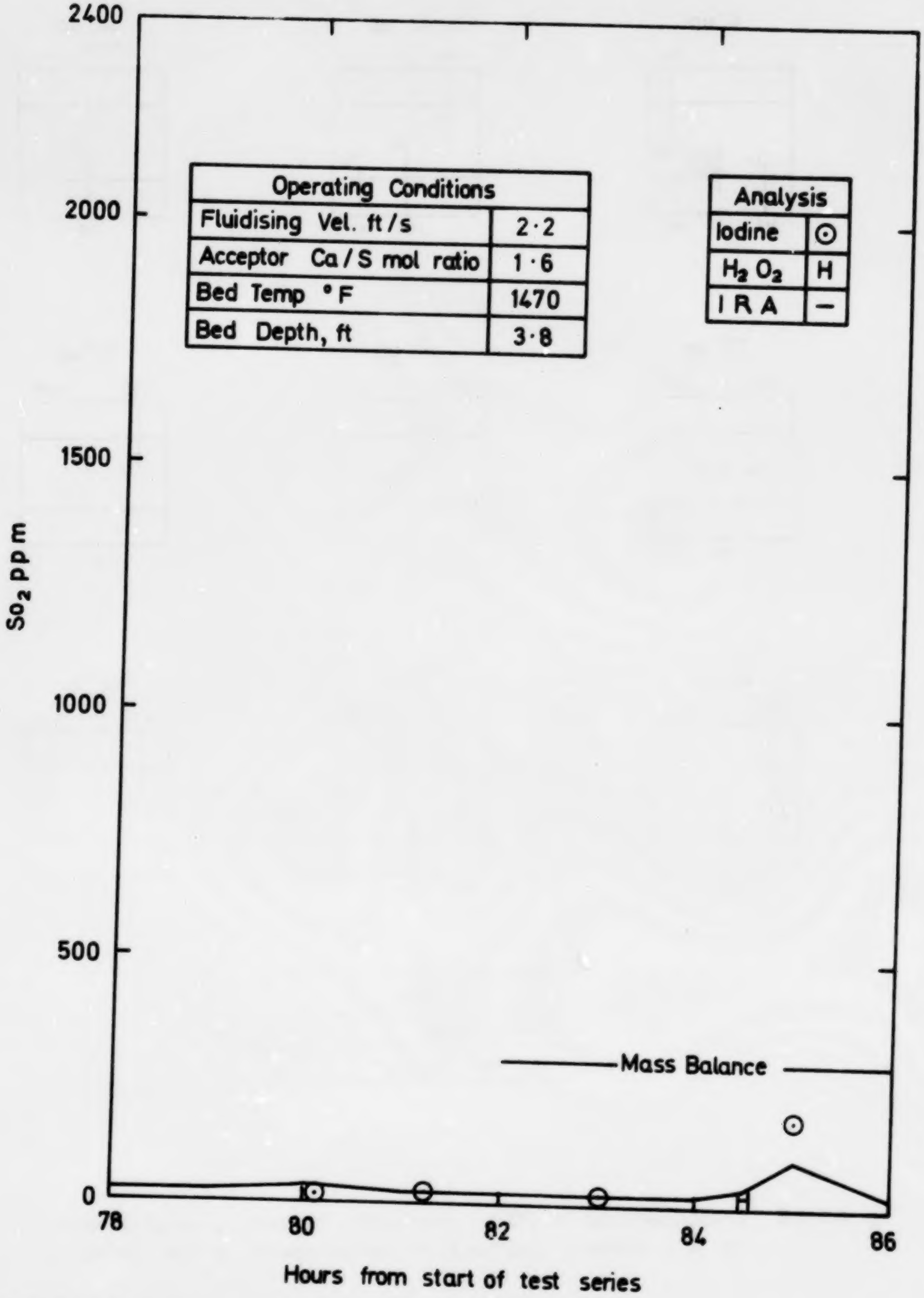
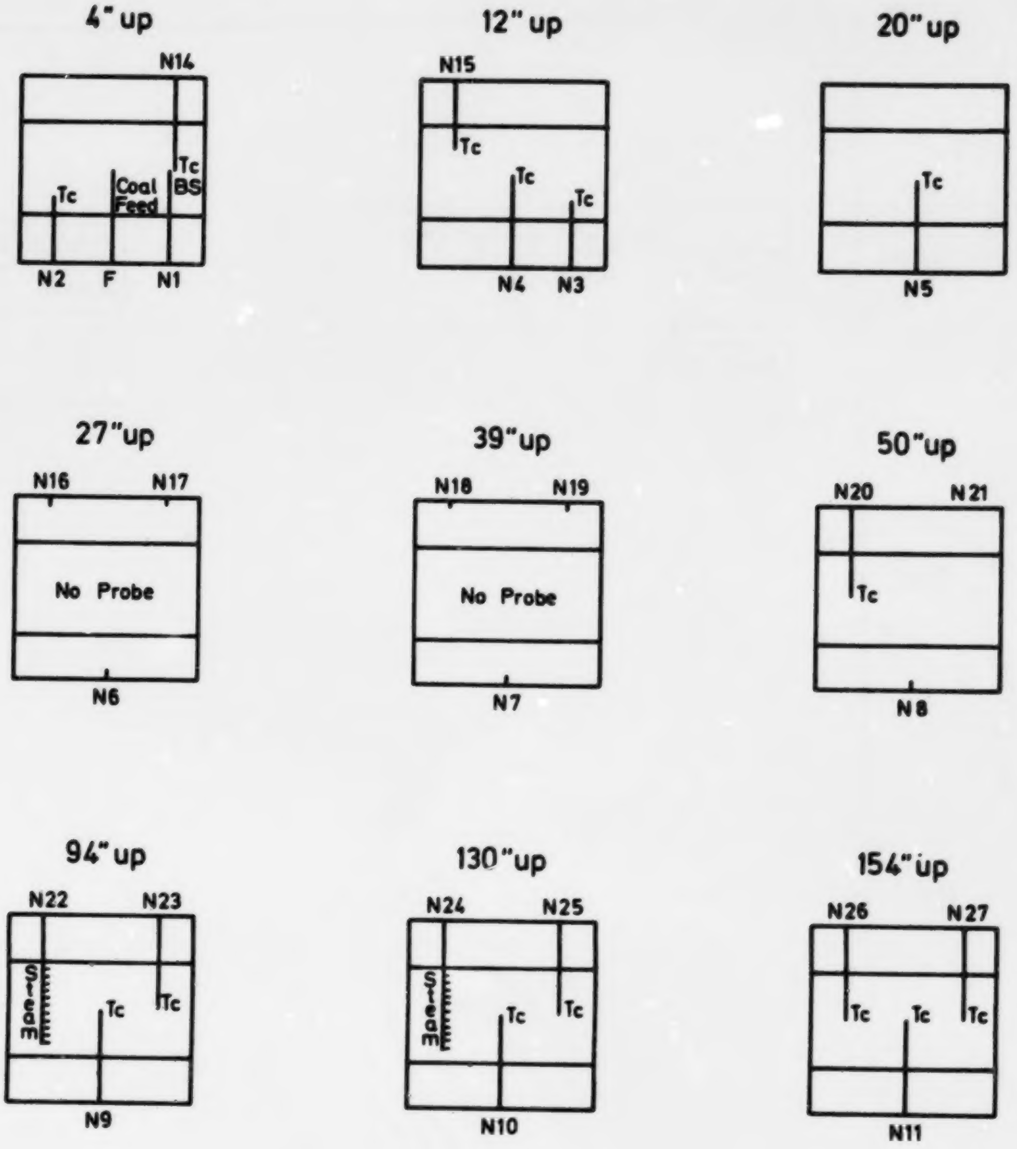


Fig. A1.4.7. So$_2$ concentrations in Test 4·6. Fines Recycle



Key	
Thermocouple	TC
Bed Ash Sampler	BS

Fig. A.1.4.8 Cross-sections of 36 in combustor at varying heights above air jets showing positions of thermocouples in Test Series 4

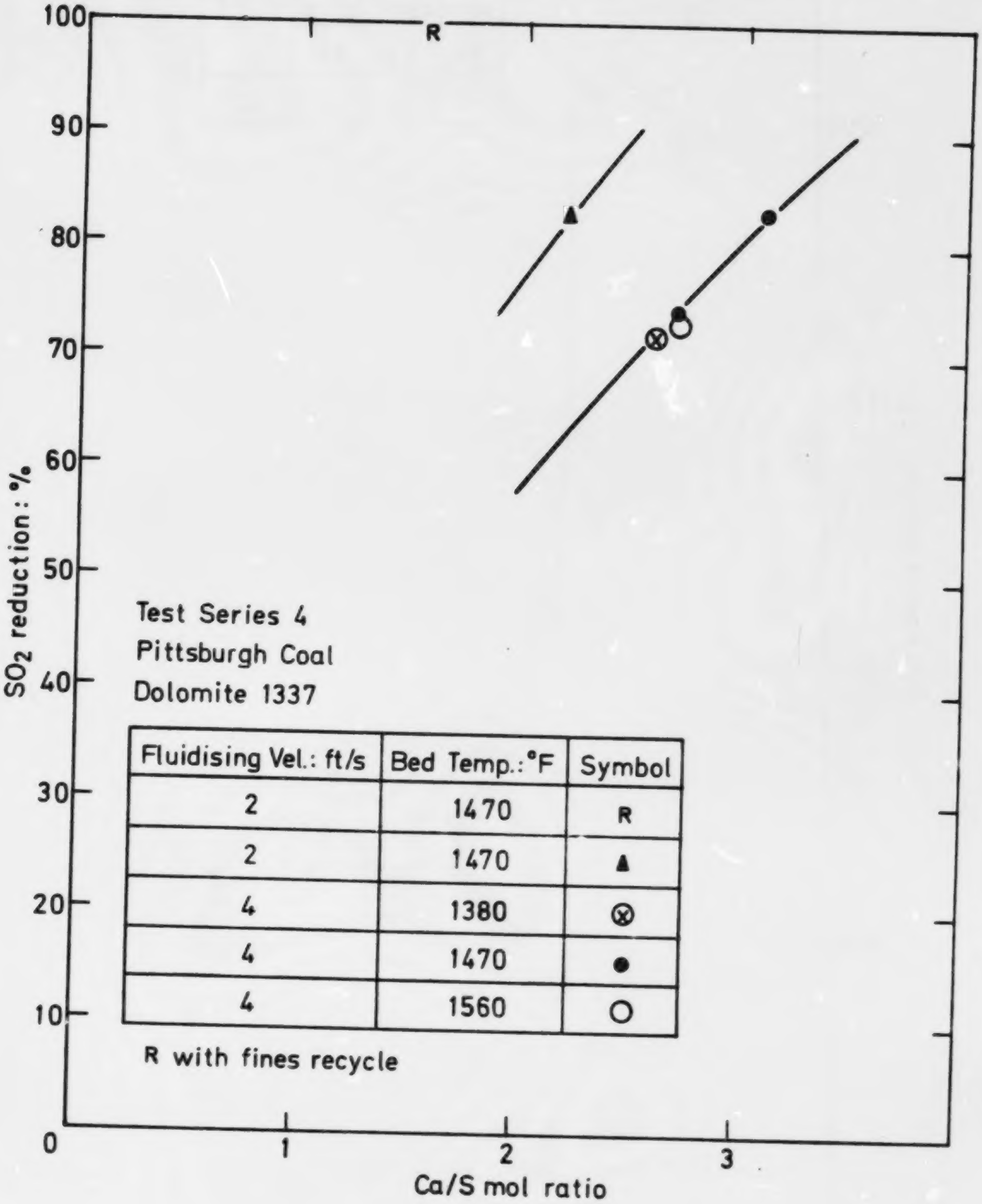


Fig. A1. 4.9. SO$_2$ reduction in Test Series 4

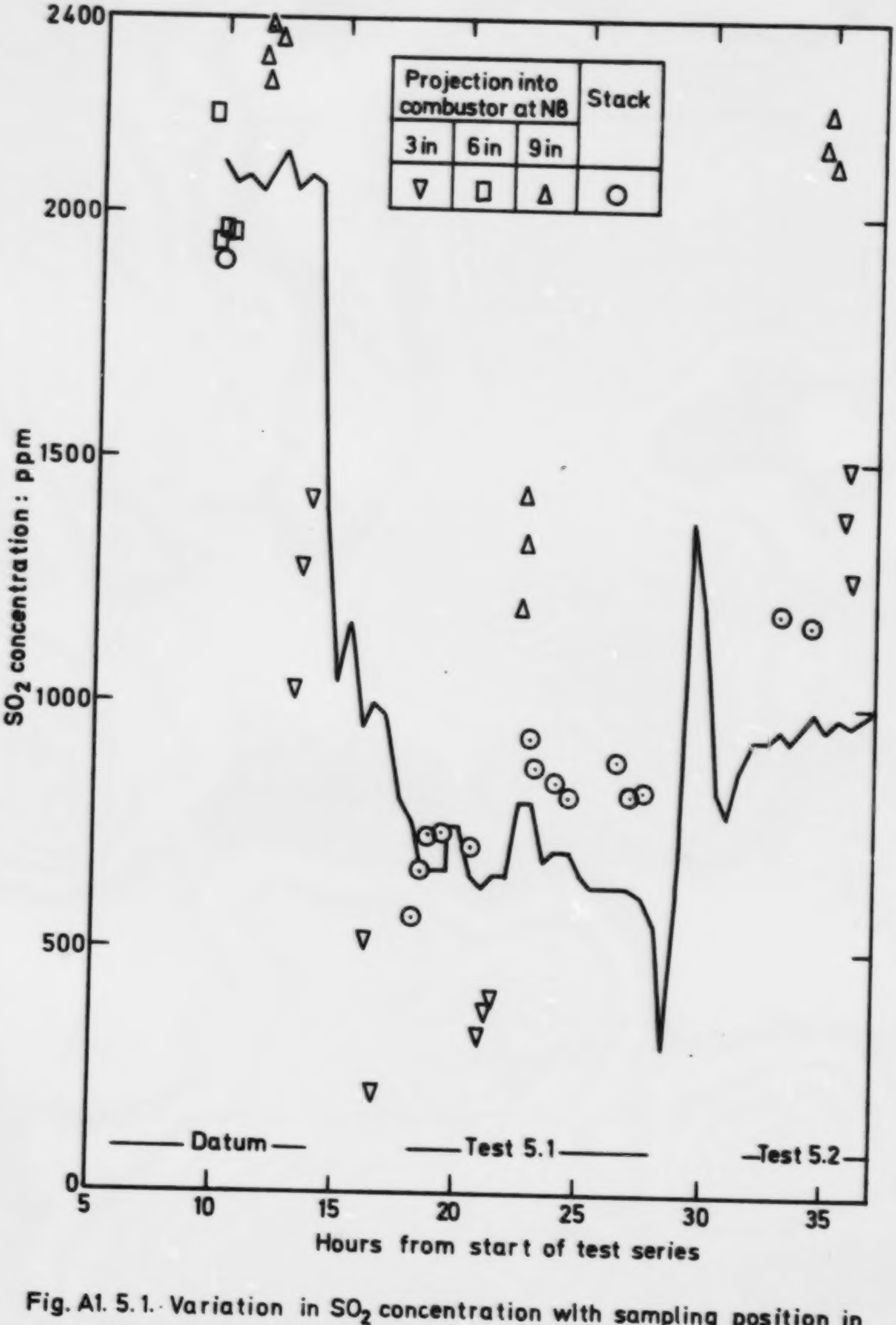


Fig. A1. 5. 1. Variation in SO$_2$ concentration with sampling position in Test Series 5 (Ca/S mol ratios of 0, 1·7 & 1·6 : 4, 4 & 8 ft/s : 1560°F : 2·1 ft bed)

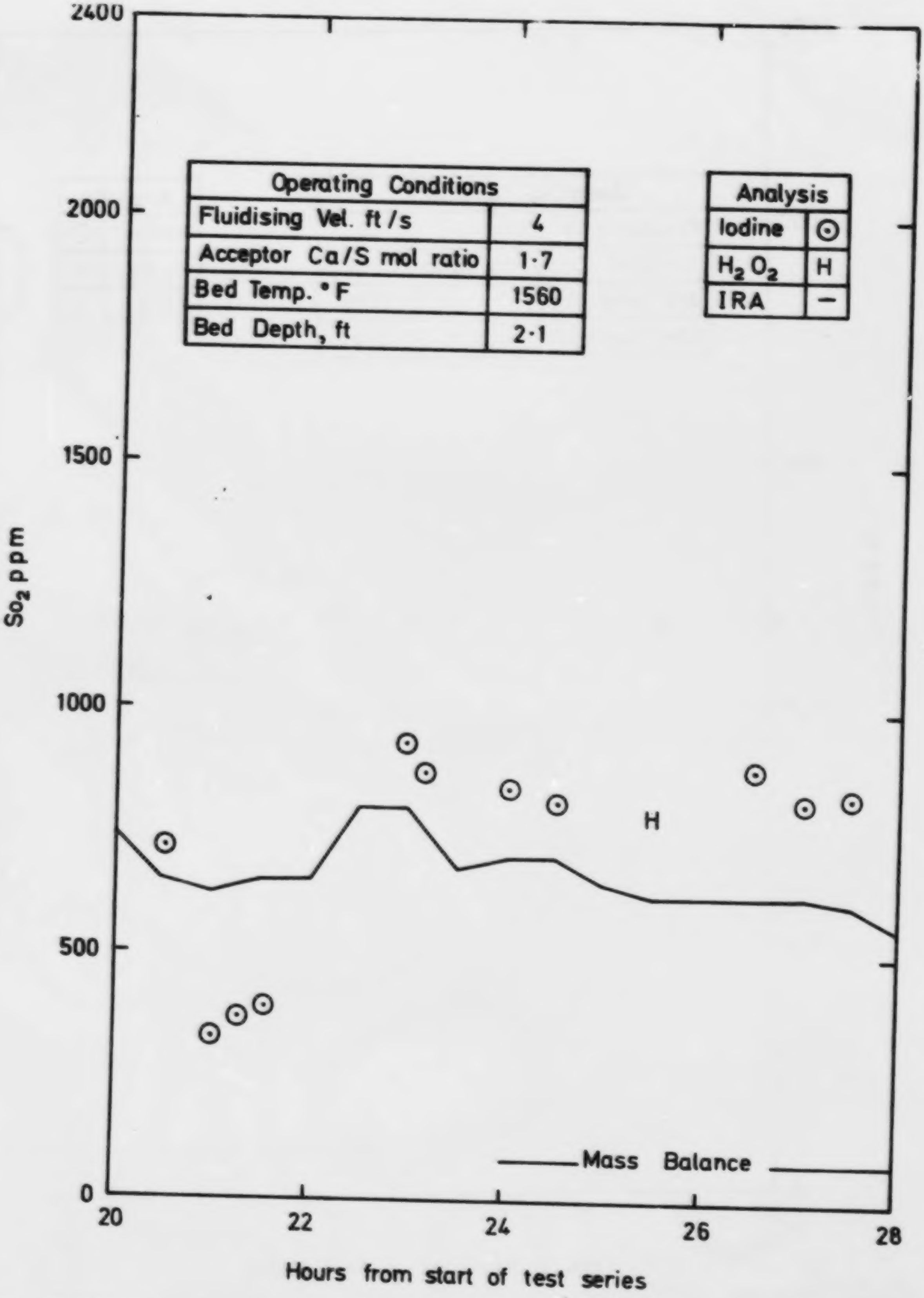


Fig. A 1.5.2. SO_2 concentrations in Test 5·1

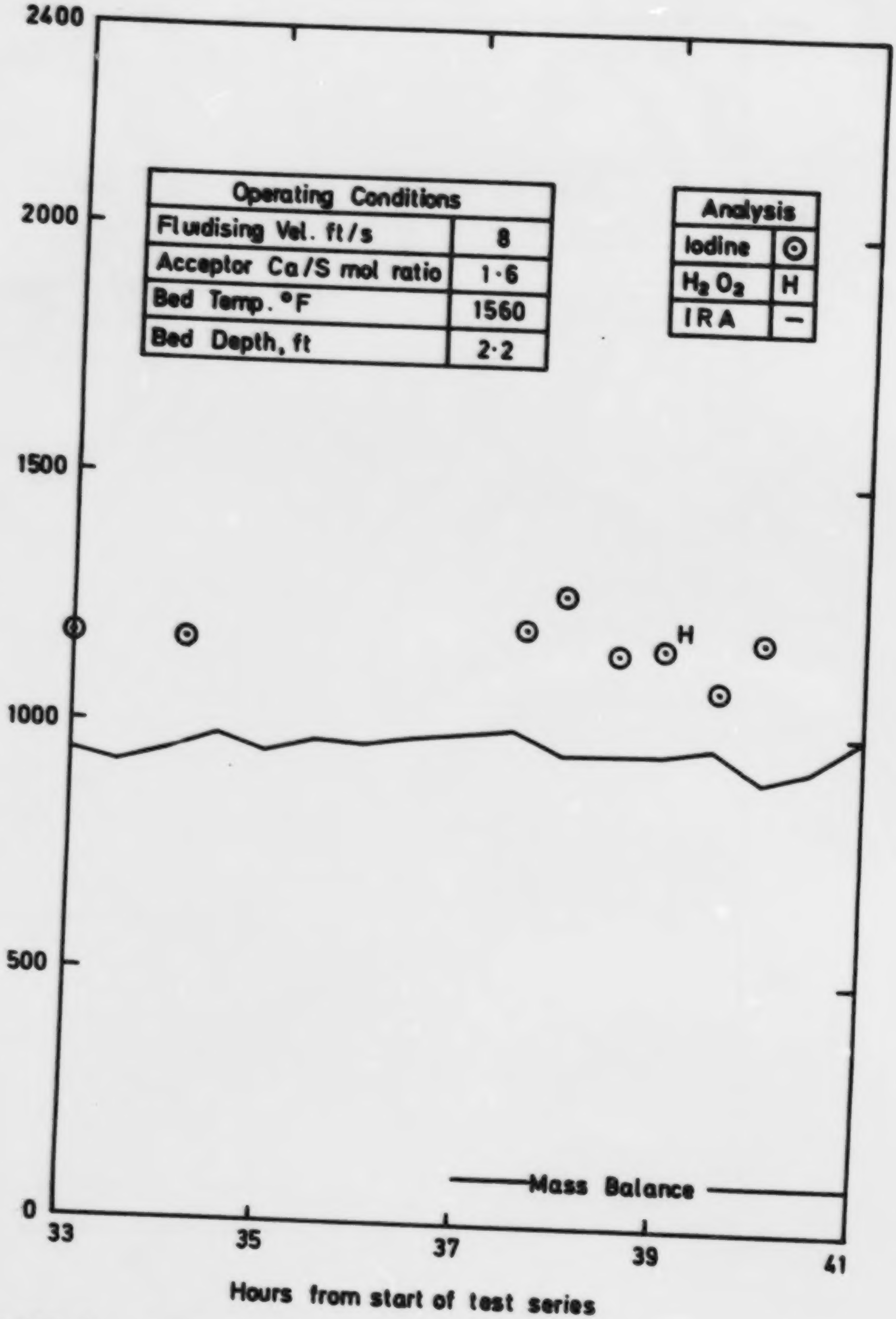


Fig. A.1.5.3 SO_2 concentrations in Test 5·2

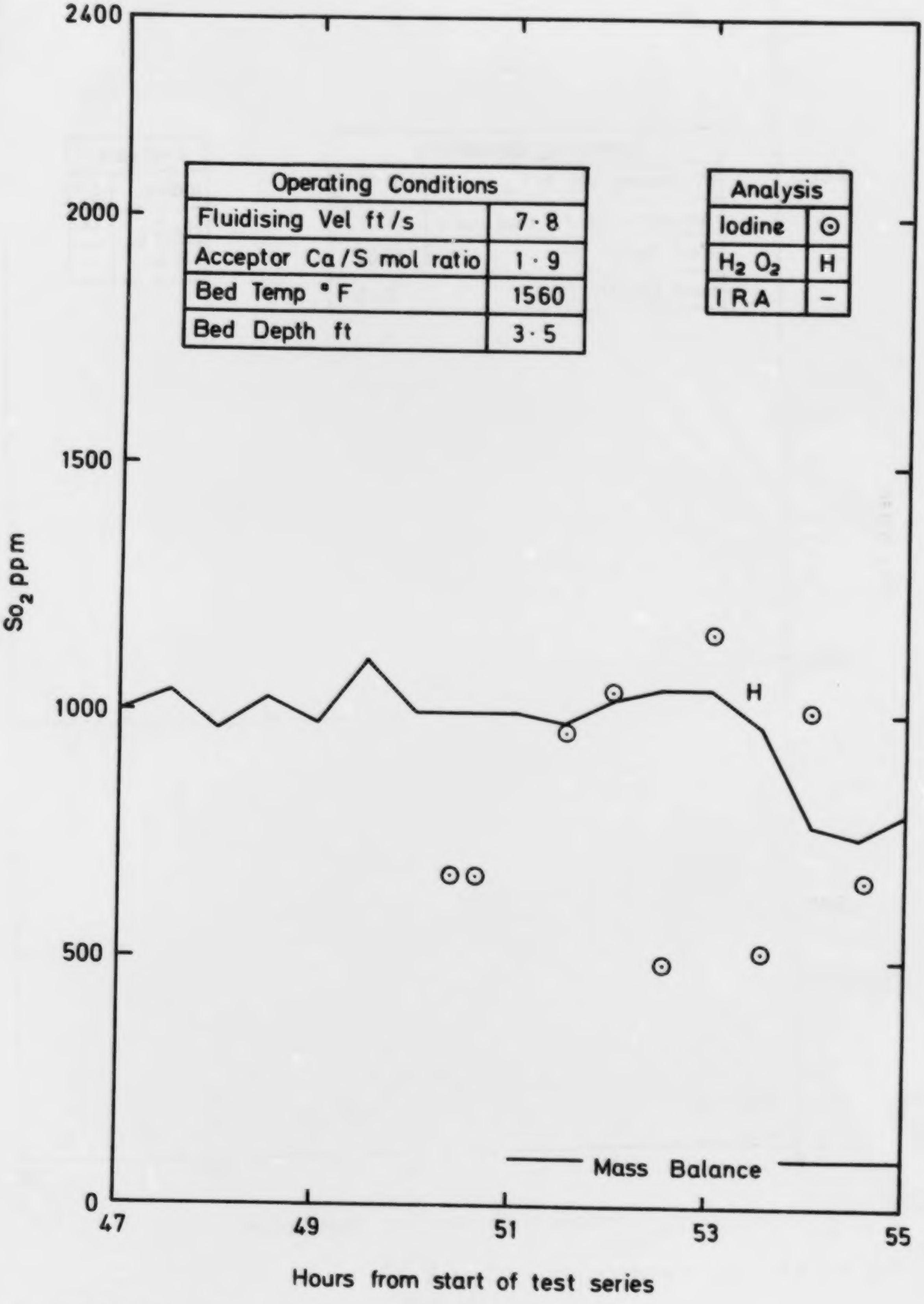


Fig. A 1.5.4. So_2 concentrations in Test 5·3

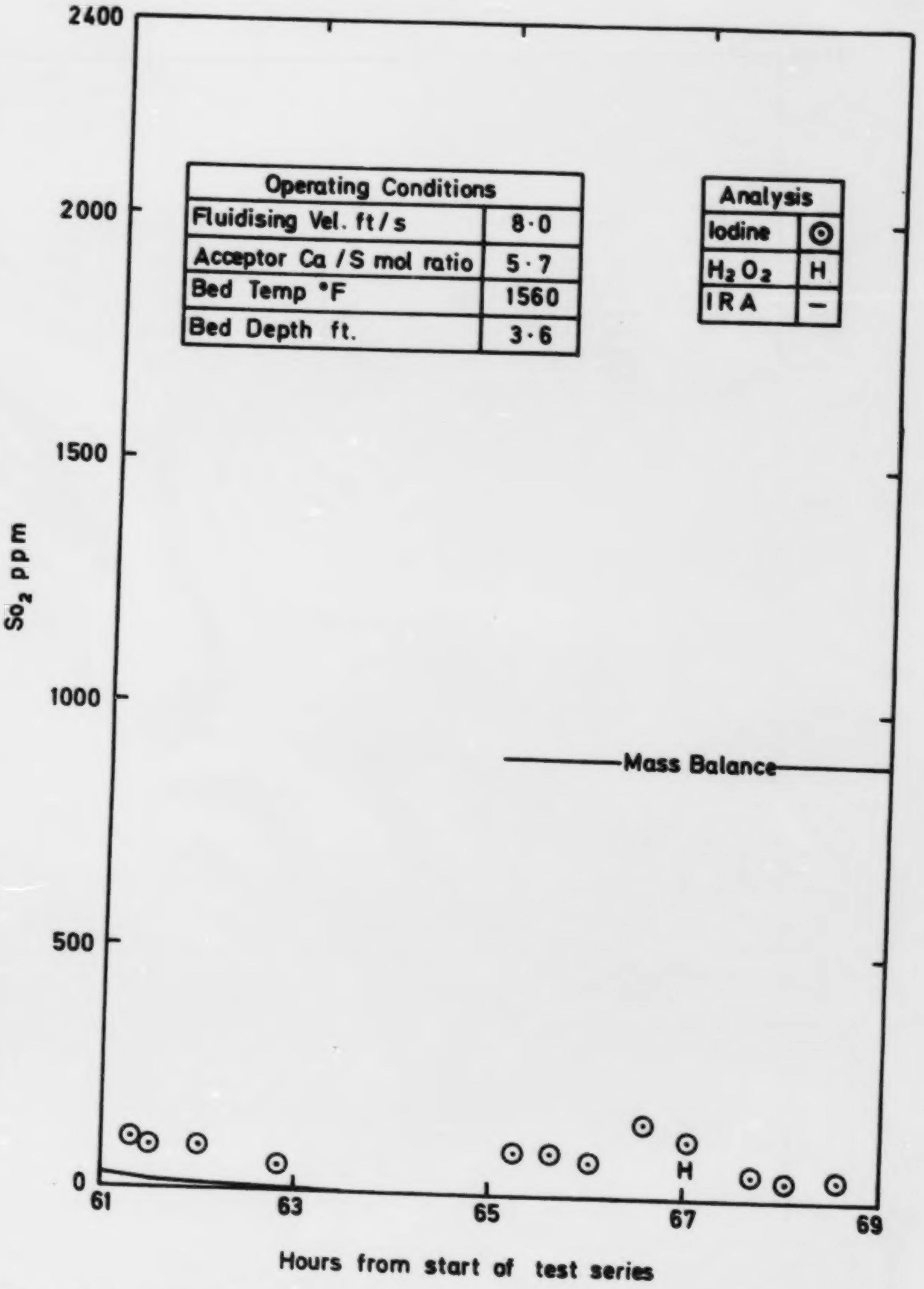


Fig. A 1.5.5. So$_2$ concentration in Test.5·4

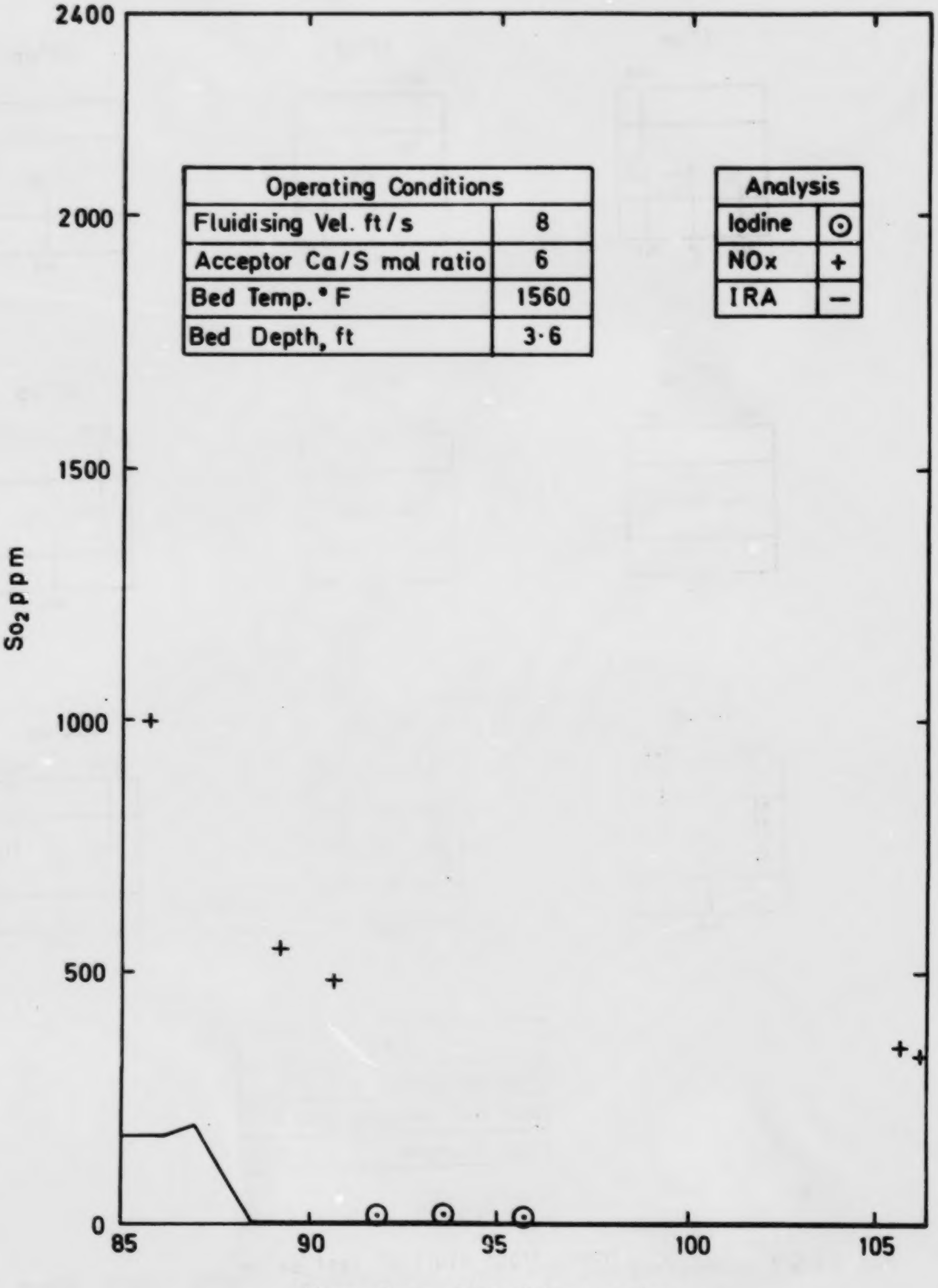
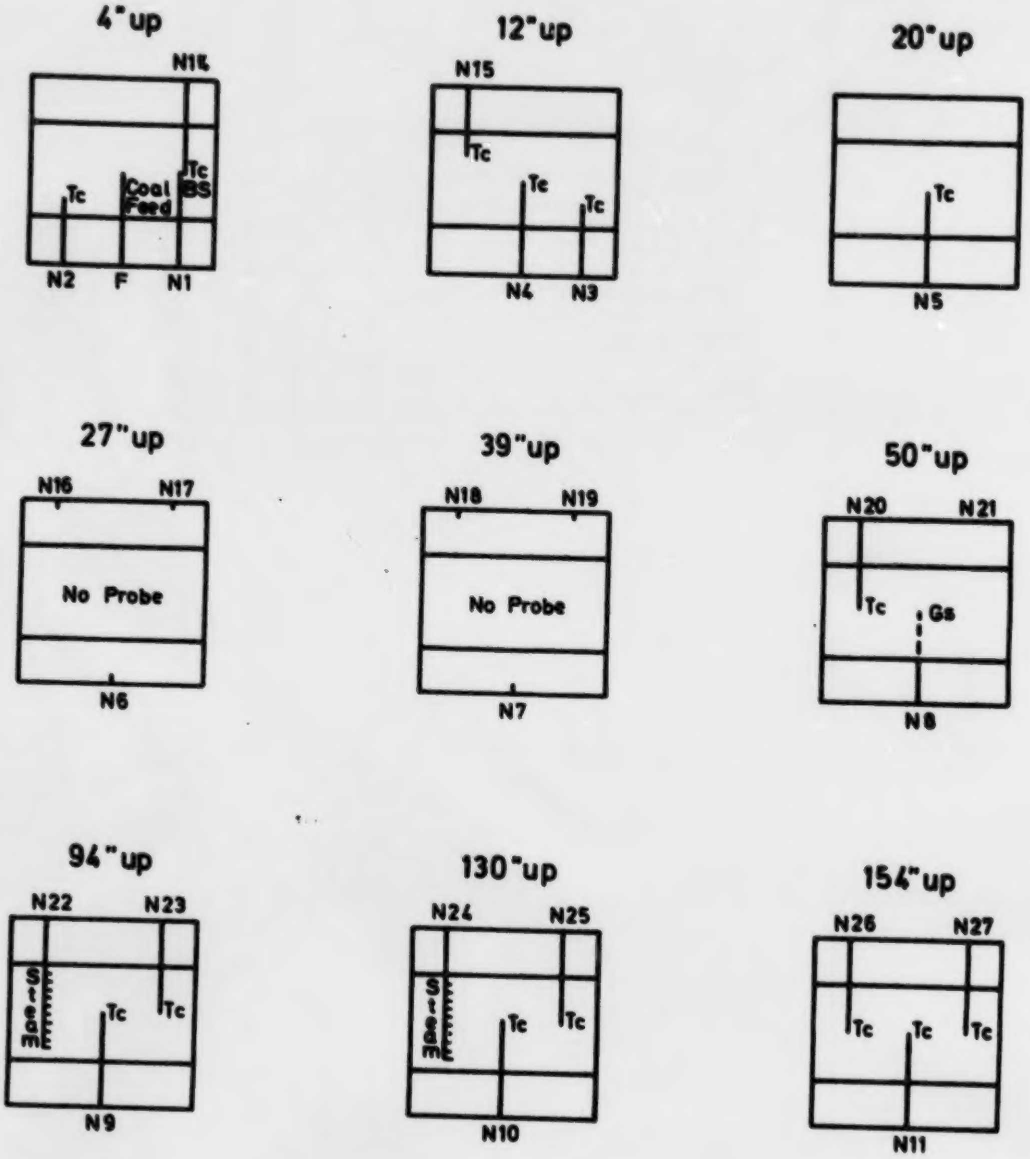
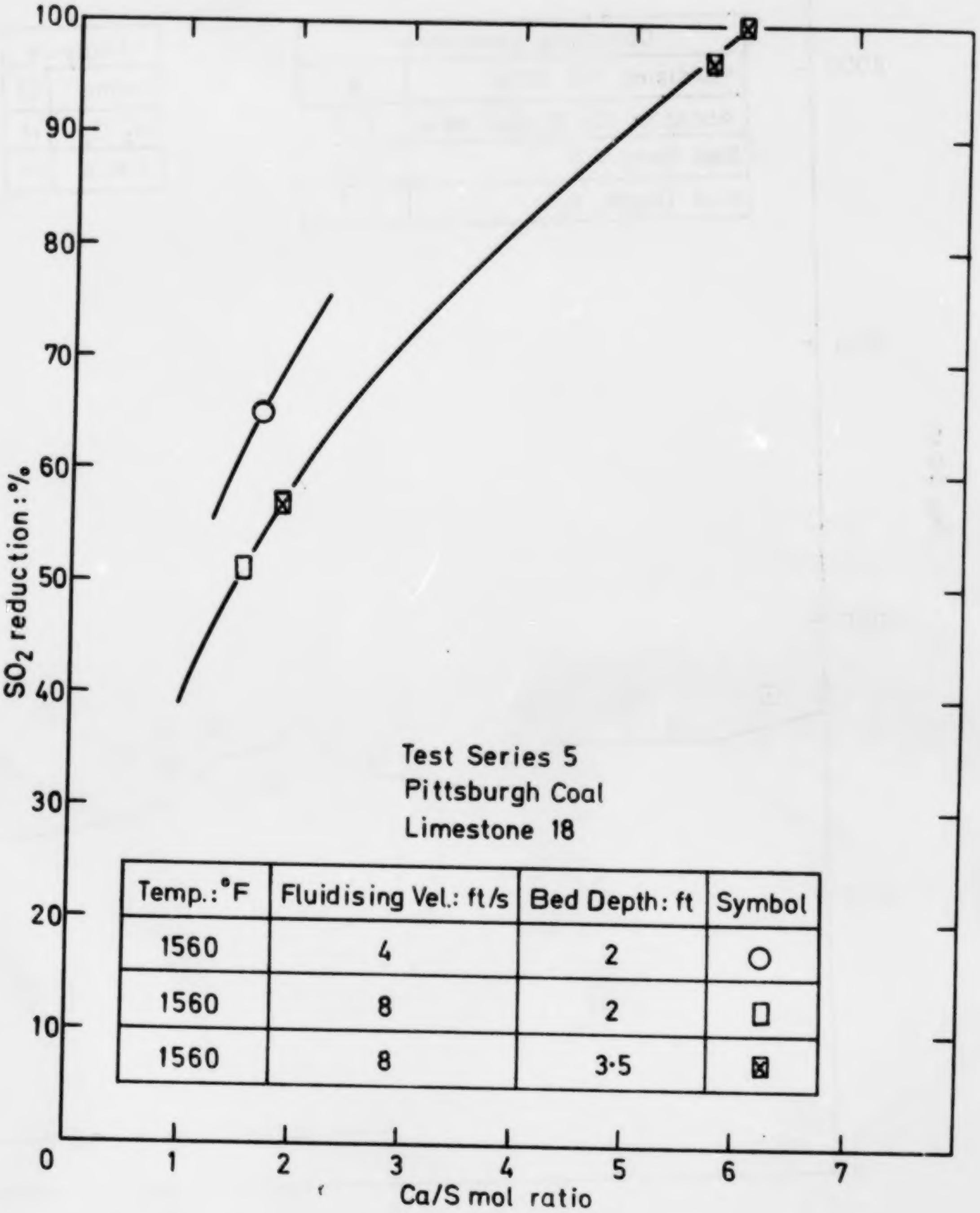


Fig. A 1.5.6. SO_2 and NO_x concentrations in test 5·5



Key	
Thermocouple	T C
Bed Ash Sampler	B S
Gas Sampler	G S

Fig. A.1.5.7. Cross-sections of 36 in combustor at varying heights above air jets showing positions of thermocouples in Test Series 5



Temp.: °F	Fluidising Vel.: ft/s	Bed Depth: ft	Symbol
1560	4	2	○
1560	8	2	☐
1560	8	3·5	☒

Fig. A1. 5. 8. SO_2 reduction in Test Series 5

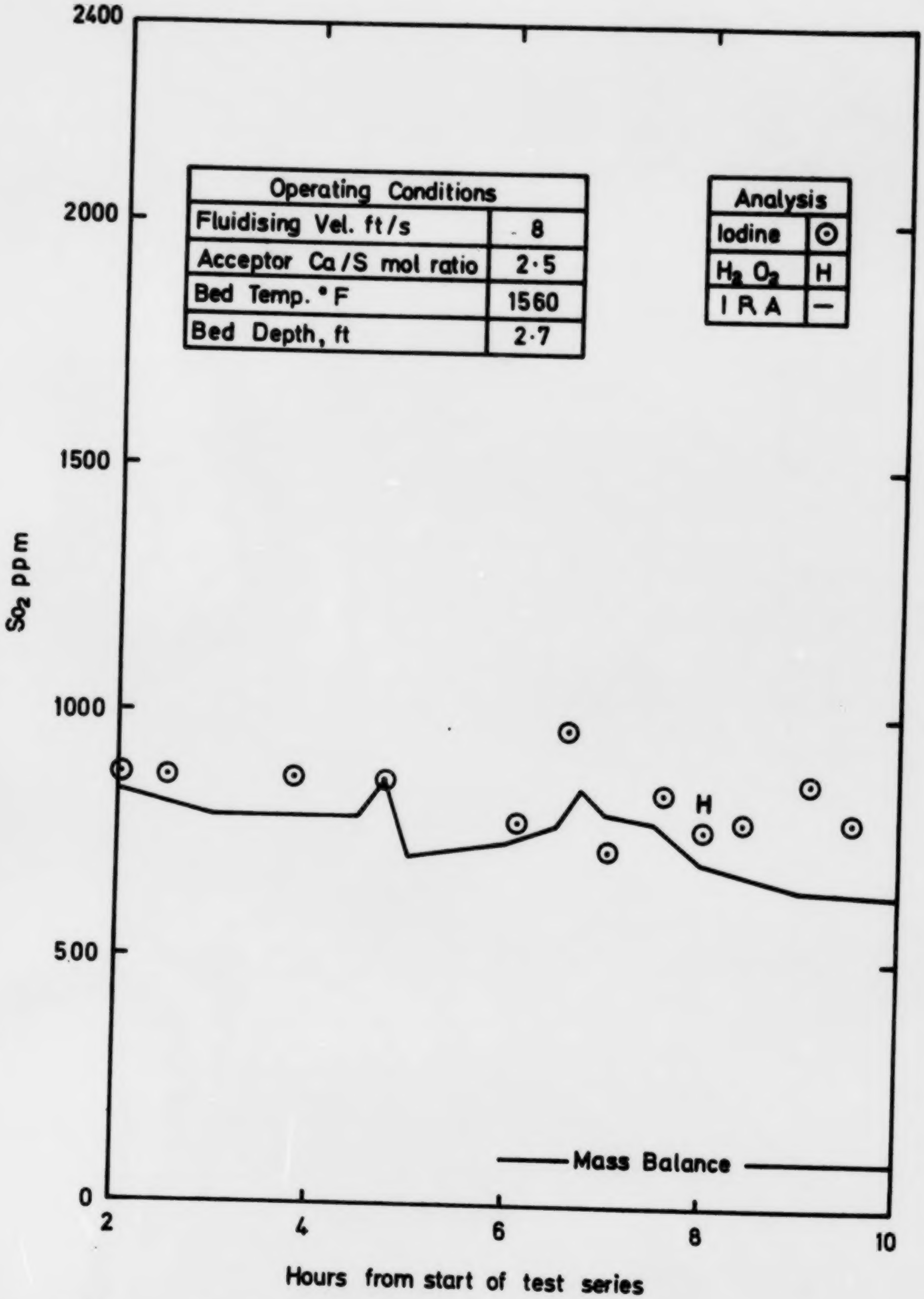


Fig. A1.6.1. SO_2 concentrations in Test 6·1

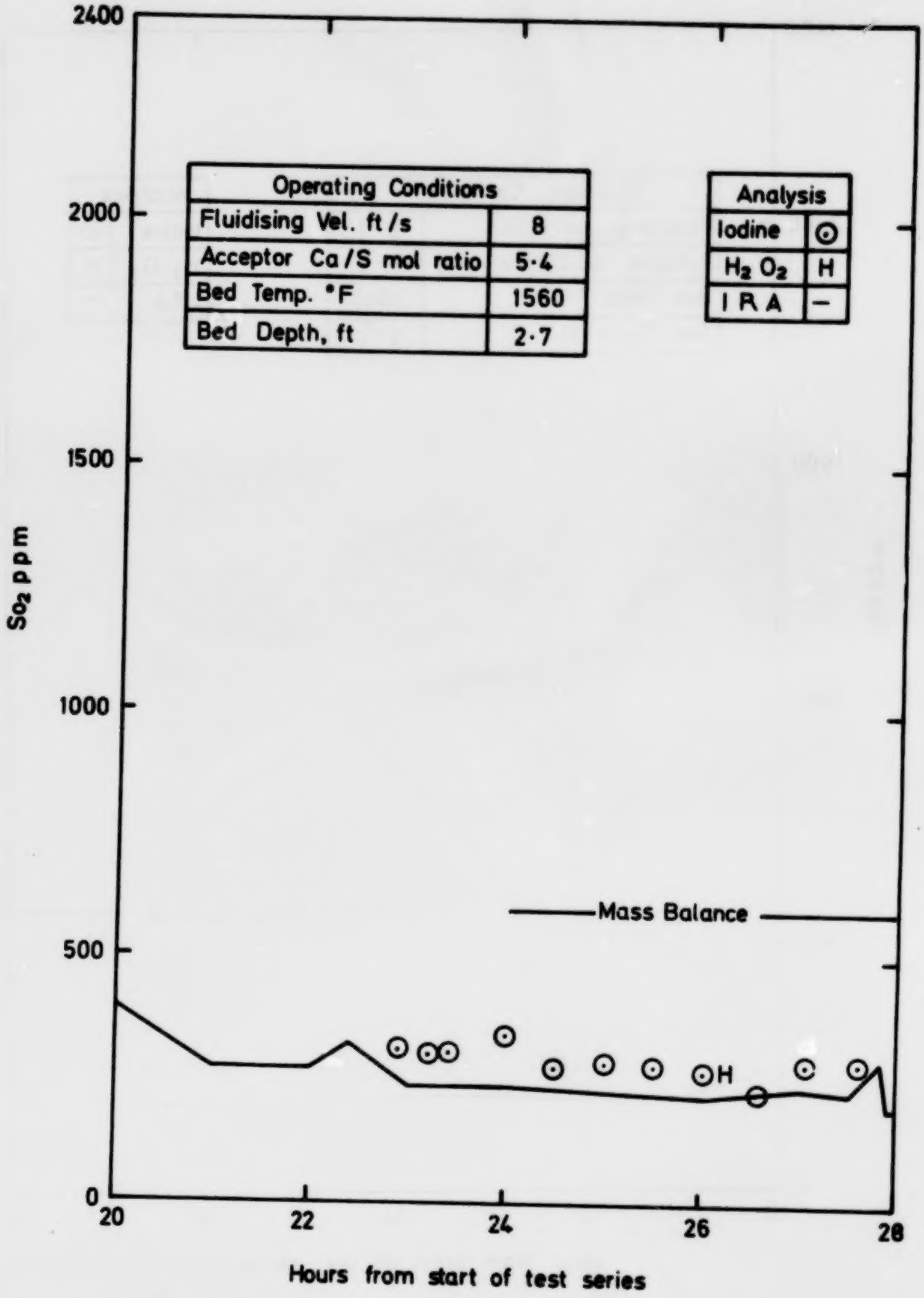


Fig. A1. 6.2. SO_2 concentrations in Test 6·2

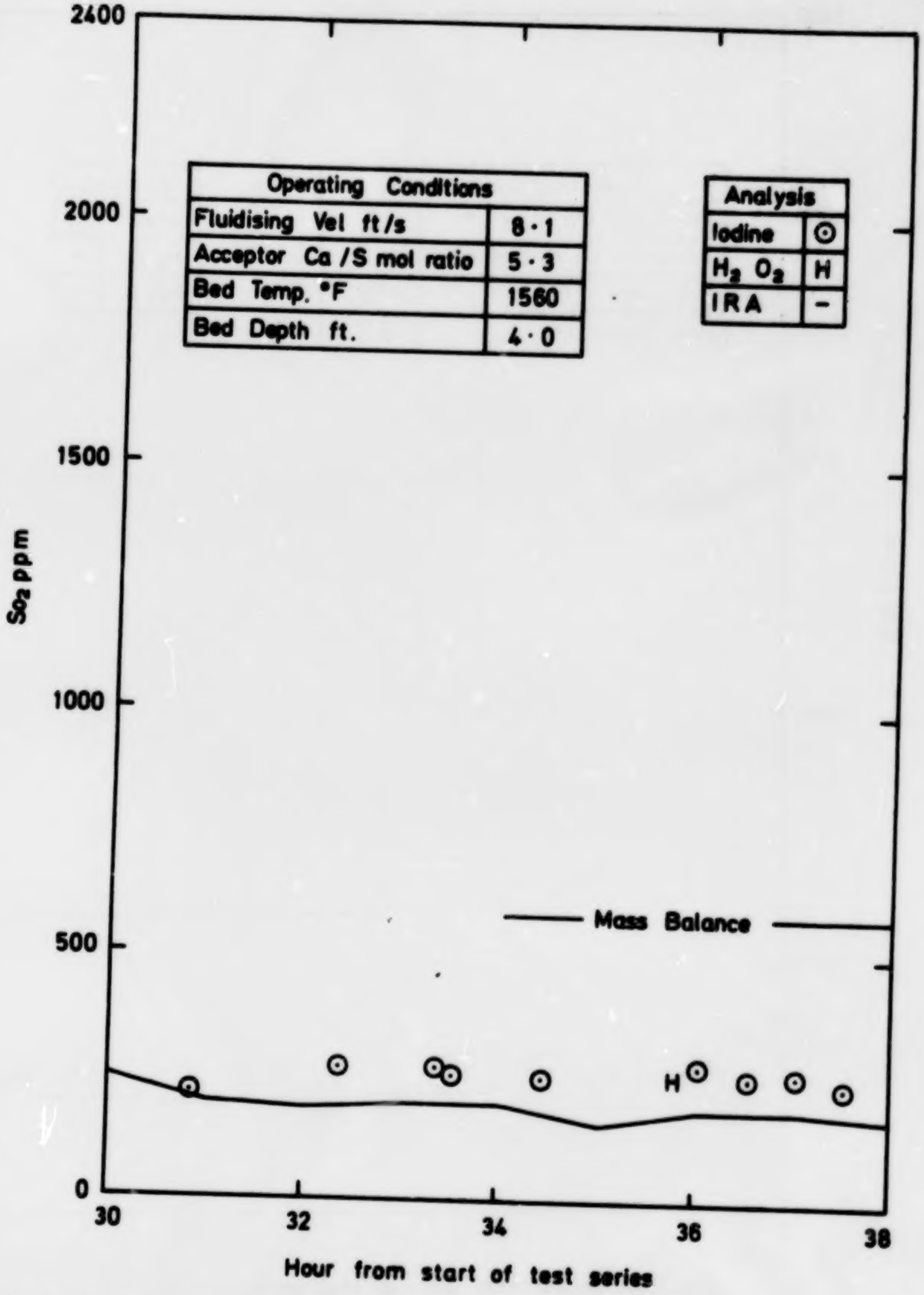


Fig. A 1.6.3. SO_2 concentrations in Test 6·3

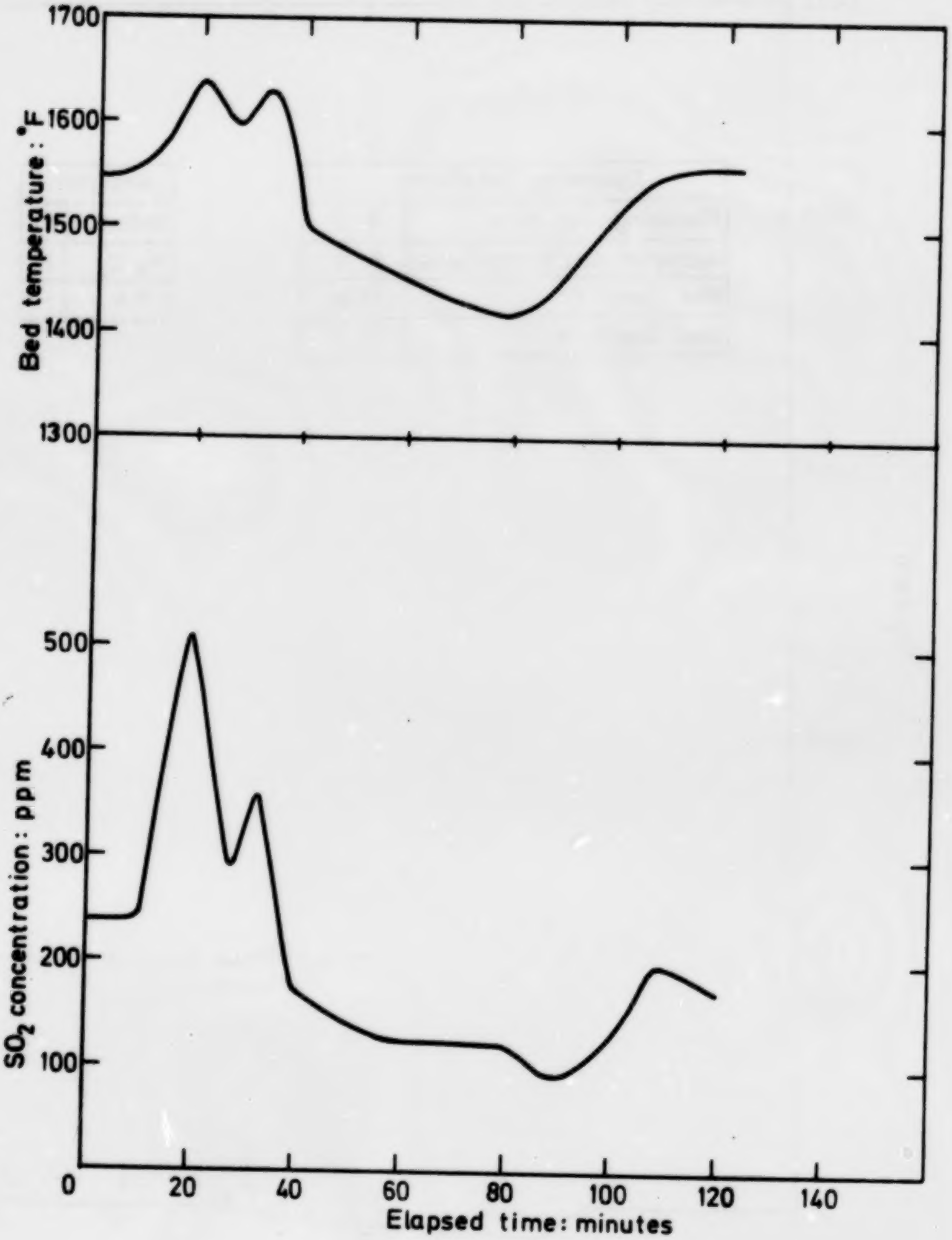
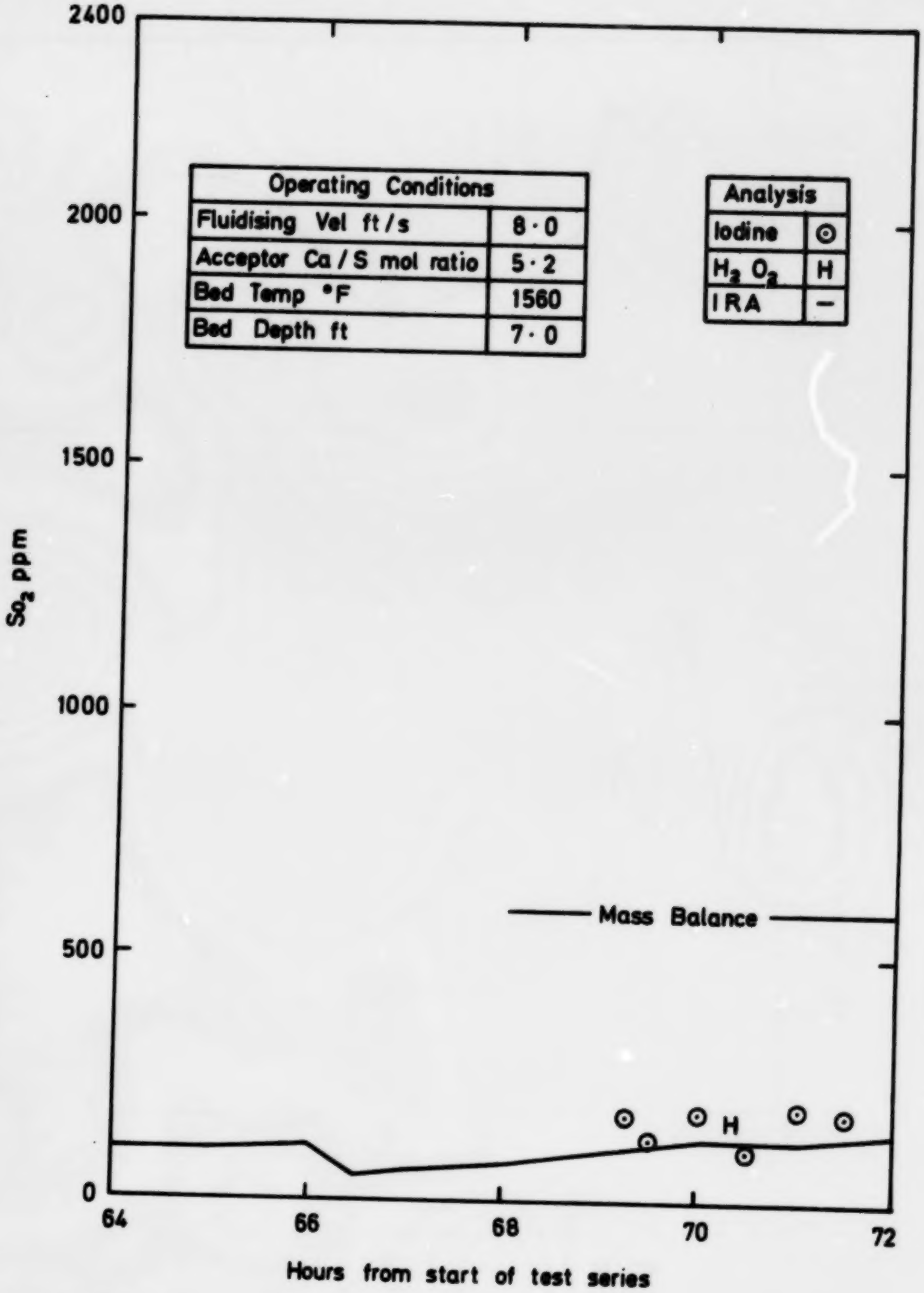


Fig. A1. 6. 4. SO$_2$ concentrations and bed temperatures during bed temperature survey (Ca/S mol ratio of 5·3: 8ft/s: 4ft bed)



Operating Conditions	
Fluidising Vel ft/s	8·0
Acceptor Ca/S mol ratio	5·2
Bed Temp °F	1560
Bed Depth ft	7·0

Analysis	
Iodine	⊙
H_2O_2	H
IRA	—

Fig. A 1.6.5. SO_2 concentrations in Test 6·4

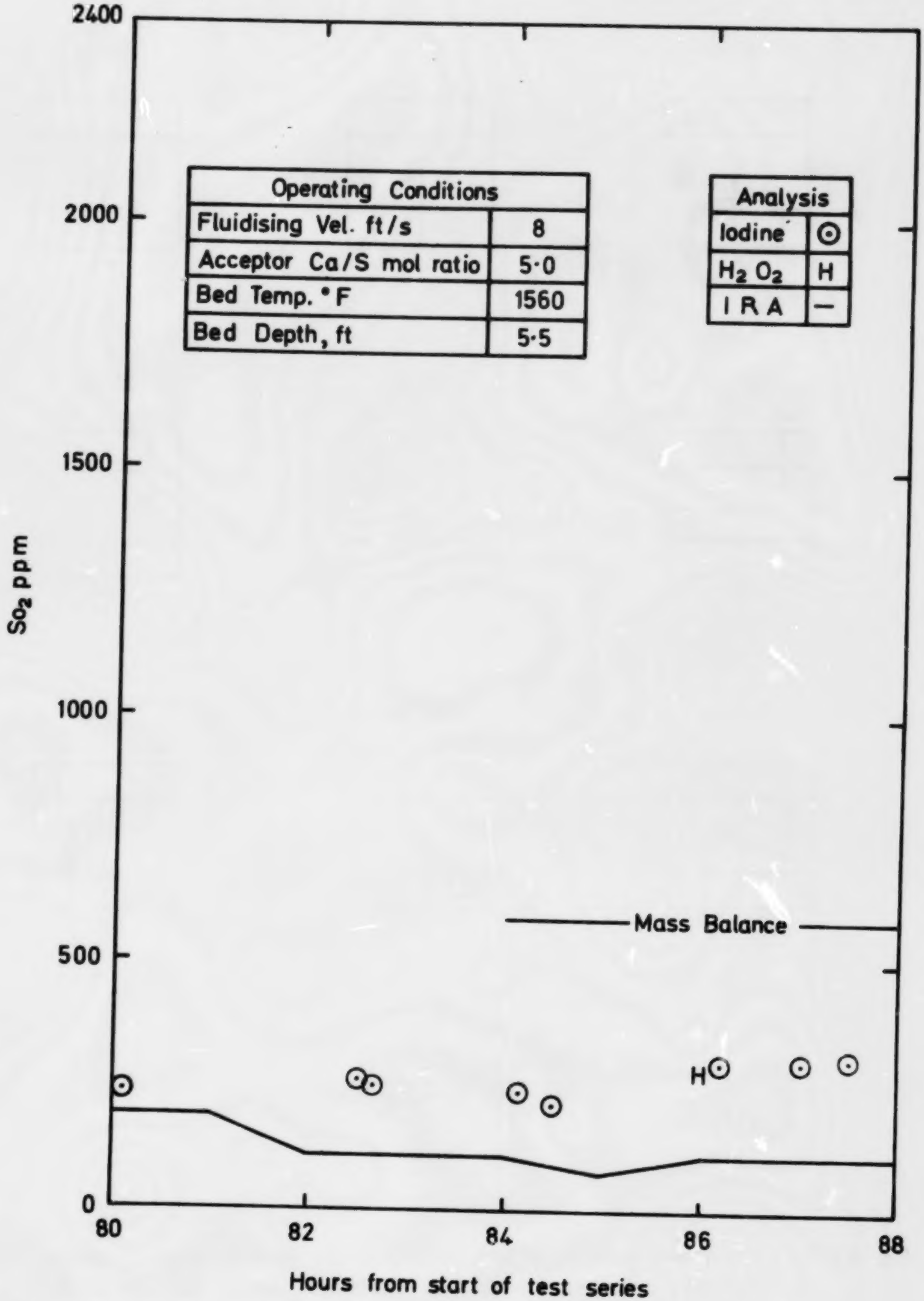


Fig. A1.6.6. So$_2$ concentrations in Test 6·5

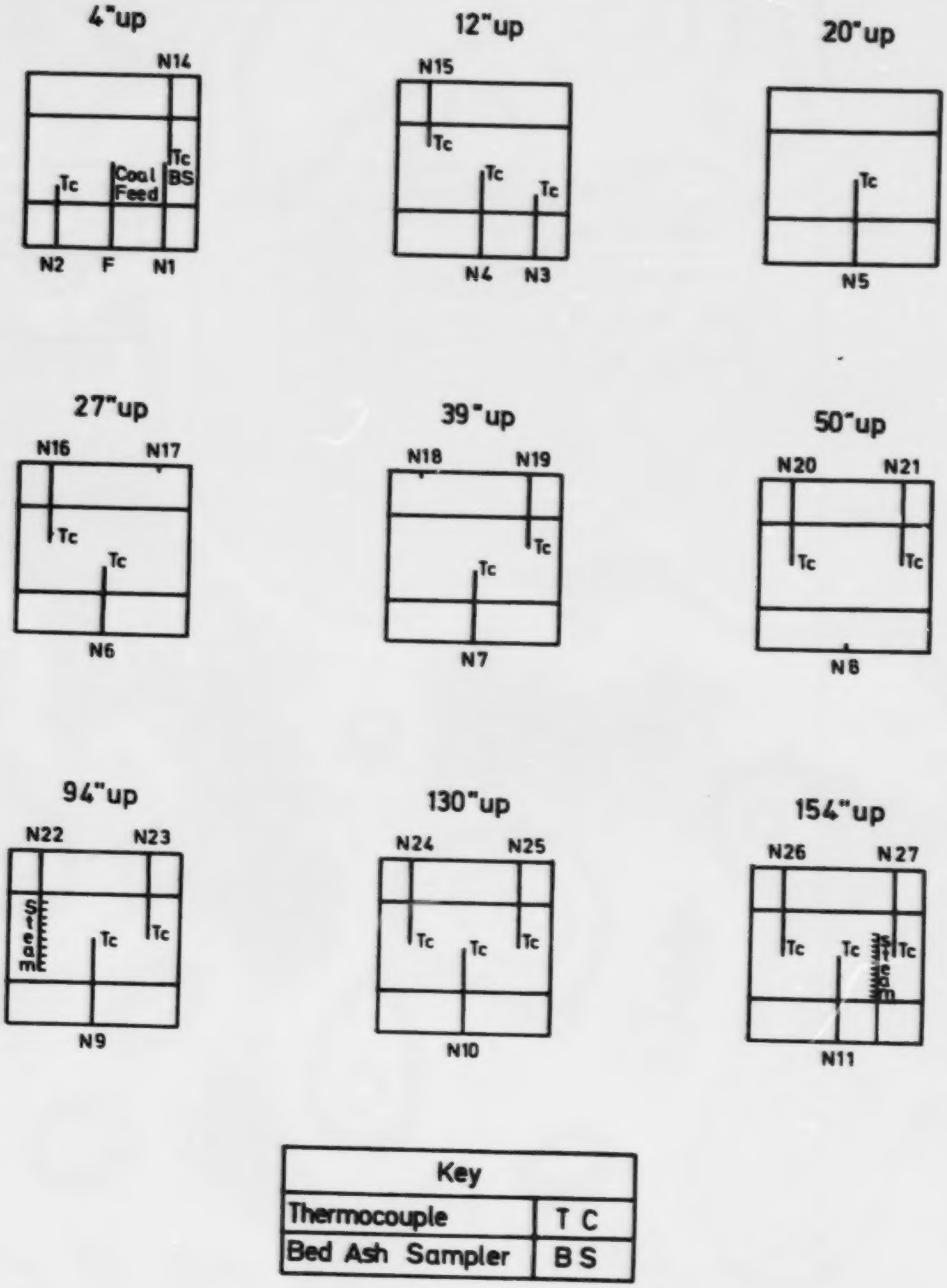


Fig. A.1.6.7. Cross-sections of 36 in combustor at varying heights above air jets showing positions of thermocouples in Test Series 6

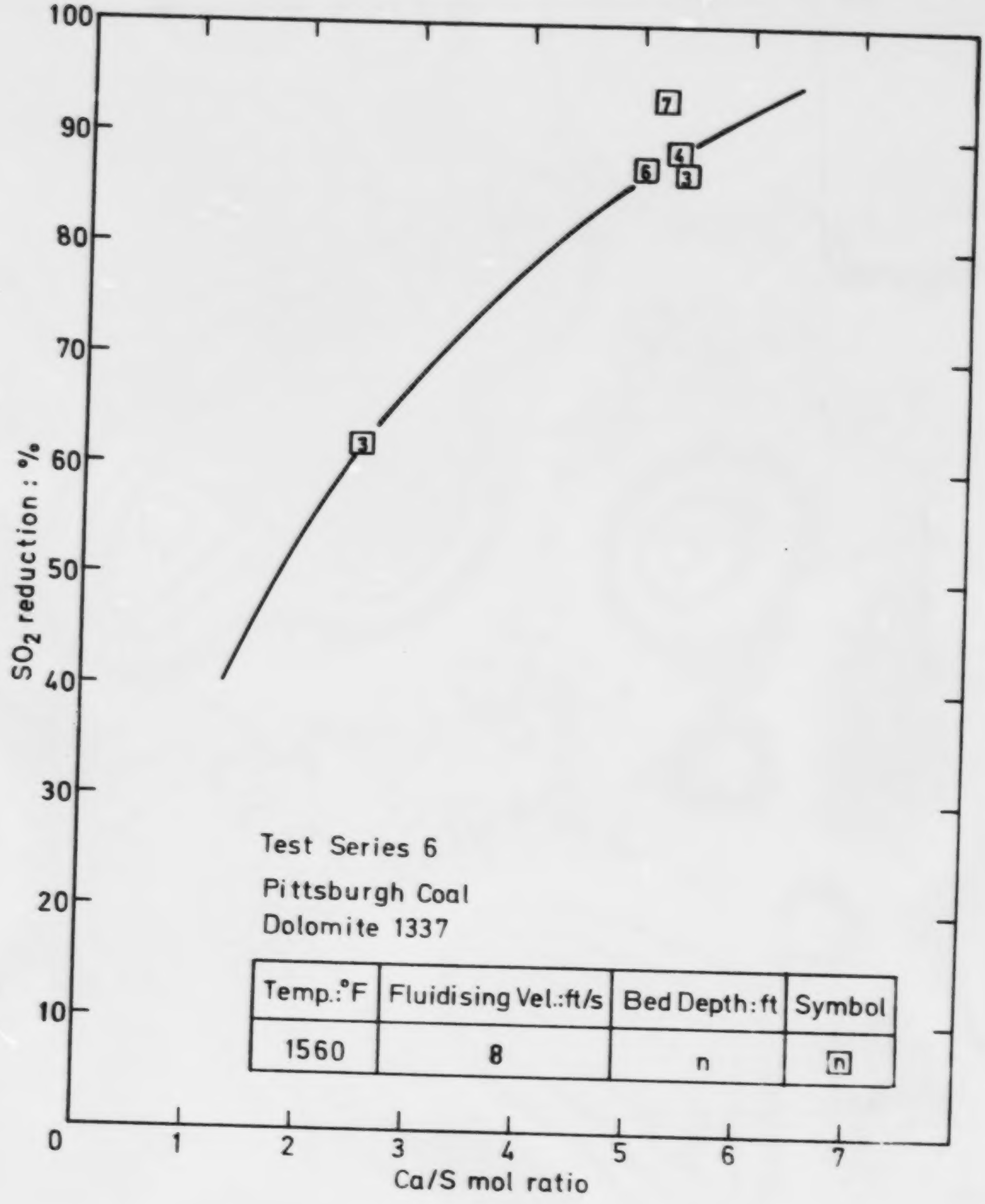


Fig. A1. 6. 8. SO$_2$ reduction in Test Series 6

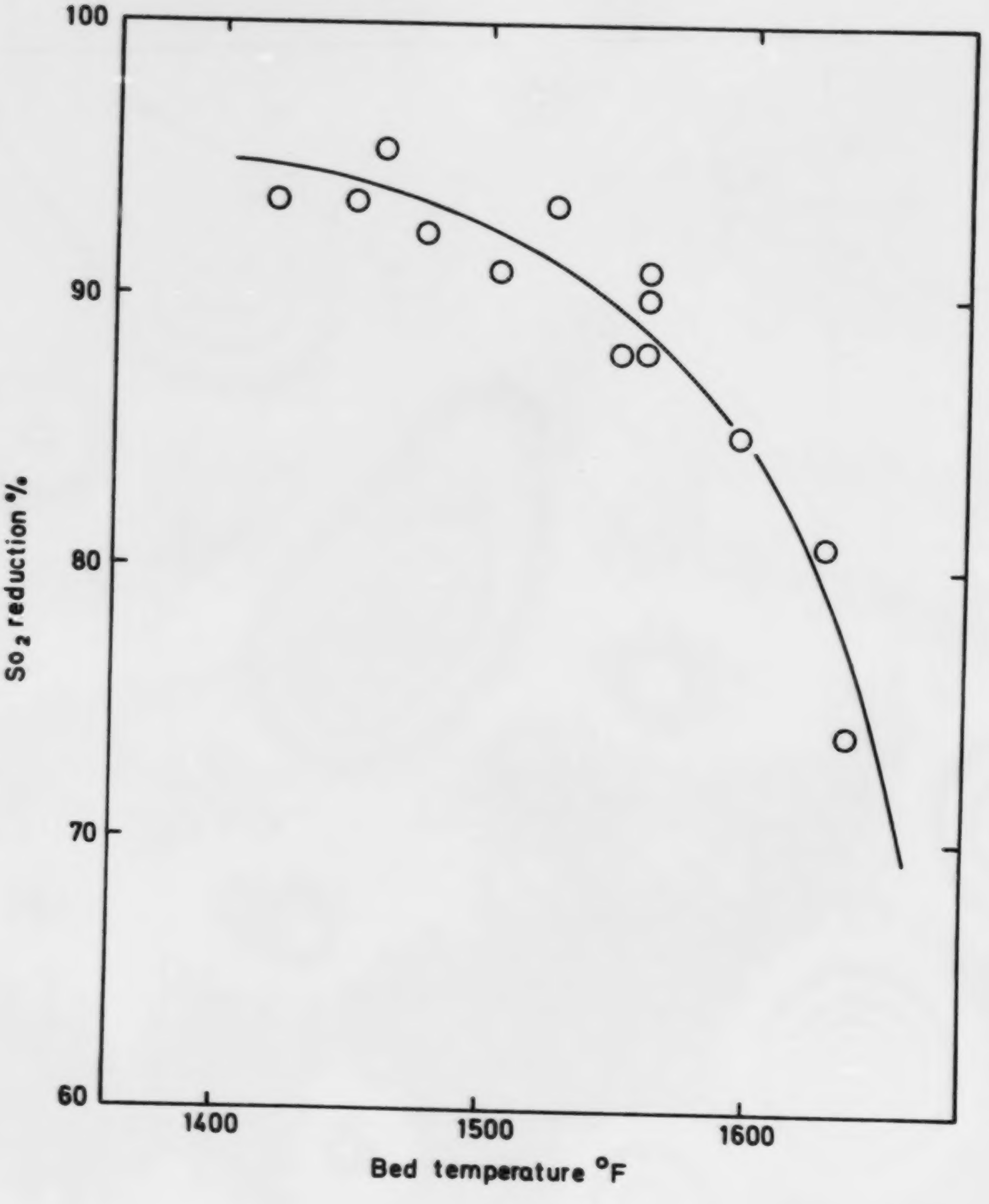


Fig. A 1.6.9. SO_2 reduction during bed temperature survey

NATIONAL COAL BOARD

FINAL REPORT

JUNE 1970 - JUNE 1971

REDUCTION OF ATMOSPHERIC POLLUTION

APPENDIX 2. EXPERIMENTS WITH THE 48 IN x 24 IN PRESSURISED COMBUSTOR. (TASK II)

PREPARED FOR

ENVIRONMENTAL PROTECTION AGENCY
OFFICE OF AIR PROGRAMS
411 WEST CHAPEL HILL STREET
DURHAM, NORTH CAROLINA 27701

REFERENCE NO. DHB 060971

SEPTEMBER 1971

A 2.i

FLUIDISED COMBUSTION CONTROL GROUP

NATIONAL COAL BOARD
LONDON, ENGLAND

REDUCTION OF ATMOSPHERIC POLLUTION

Research on reducing emission of sulphur oxides, nitrogen oxides and particulates by using fluidised bed combustion of coal

Appendix 2. Experiments with the 48 in x 24 in pressurised combustor. (Task II)

Main objective

To obtain, for operation under pressure, data on (i) the emission of sulphur and nitrogen oxides and (ii) corrosion/deposition of boiler metal and turbine blade specimens.

Report prepared by: A.G. Roberts
J.E. Stantan
D.M. Wilkins

Report approved by: A.D. Dainton and
H.R. Hoy

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FOREWORD

This Appendix describes experimental work carried out using the 48 in x 24 in pressurised combustor at BCURA, between June 1970 and June 1971, as Task II of the joint N.C.B./O.A.P. research programme. The objective of Task II was to obtain, for operation under pressure, data on (i) the emission of sulphur and nitrogen oxides and (ii) corrosion/deposition of boiler metal and turbine blade specimens. A summary of the work is presented in the main report and the results are discussed there, together with results from other pilot plants.

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(Note that when referring to Tables and Figures in the text the prefix A.2 is omitted).

1. DESCRIPTION OF PLANT

1.1 General

A flow diagram of the pressurized combustion rig and its ancillary equipment is shown in Fig. 2.1; details of the construction of the combustor are given in Fig. 2.2. The combustion vessel was a refractory-lined shaft of approx. 48 in x 24 in cross-section, 10ft high, housed in a cylindrical steel shell, 22 ft long x 6 ft diameter having domed ends and capable of withstanding an internal pressure of up to 100 p.s.i.g. The walls of the shaft, which were lined with a 3 in thick lightweight insulation refractory,acted mainly as a temperature barrier and were intended to withstand a pressure differential of about ± 5 p.s.i.

The base of the combustor was closed by an air distributor plate of ⅜ in En58b steel, fitted with 465 bubble caps on a 1½ in square pitch. Each bubble cap had four horizontal jets, 1 in above the distributor plate, with an aggregate area of 1.3% of the shaft cross-section.

The bed normally contained about 1800 lb coal ash, and with a fluidising velocity of 1.8 to 2.0 ft/s had an expanded depth of about 45 in. Immersed in the bed were 65 hairpin loops of 1 in o.d. x 16 s.w.g. En58b steel tubing cantilevered from the 4 ft side walls. The hairpins formed a staggered pattern of 17 rows of 7 or 8 tubes per row, with horizontal and vertical pitches of approximately 6 in and 1½ in respectively (Fig. 2.3). Six of the hairpins, with a surface area of 6.3 ft^2, were used for air preheating and six air-cooled corrosion specimen assemblies (6.2 ft^2 total surface) formed part of a further six hairpins: the hot air from these assemblies was fed with the preheated air to the plenum chamber. The remaining 53 hairpins of total external surface of 56 ft^2 were bed cooling circuits; bed temperatures were controlled by selecting water circuits giving the total cooling surface required.

Air preheated in the tubes in the bed to between 300° and 500°F, according to operating pressure, was fed to a plenum chamber below the distributor plate. Gas burners having a rating of 5 therms/h were positioned in the chamber to heat the fluidising air and hence the fuel-bed during start-up.

Coal, premixed with acceptor, was fed pneumatically in either air or nitrogen from a pressurised lock hopper system through four ½ in B.S. pipe-lines terminating at nozzles, fitted with water-cooled shrouds, projecting 5½ in into the bed through the 4 ft side walls of the combustion vessel. The nozzles were located 1 ft from each of the two 2 ft sides, at a height of about 4 in above the distributor plate.

A bank of 4 rows of uncooled horizontal 1 in o.d. En58b tubes on a nominal 3 in triangular pitch was located immediately above the upper surface of the bed (at 46 in to 54 in above the distributor plate) and parallel to the 2 ft sides of the combustor. The tube bank acted as a baffle system to minimise "splashing".

Three water-cooling circuits, having a total surface area of 16.6 ft^2, were provided in the gas space above the uncooled tube bank to control the gas temperature if excessive combustion occurred in the freeboard.

The dust-laden gas leaving the shaft passed through a 10 in diameter recirculation cyclone, suspended from the top closure plate, and the fines were returned to the bed via a dipleg terminating approximately 3 in from the distributor plate. The lower end of the dipleg was fitted with an "air slide" through which a small flow of nitrogen was passed to facilitate the downwards flow of solids. The amount of material being recycled back to the bed was unknown, but available evidence suggests that it was small and the combustor probably behaved as a non-recycle system. The partially-cleaned combustion products were passed successively through two further 10 in diameter cyclones from which collected fines were continuously removed by positive blow-down systems. Physical dimensions of the three cyclones are given in Table 2.1 and Fig. 2.4.

Combustion products leaving the second stage of dust cleaning were passed through an egg-box type flow straightener before being accelerated through the gas turbine blade cascade (Fig. 2.5). The blades were obtained from a stator segment of a Rolls Royce marine Proteus engine and were made in X40 alloy having a high cobalt content. Two 3/32 in diameter Nimonic 75 target rods were fitted in the gas stream immediately downstream of the cascade, at a point where the Mach number was about 0.6, to simulate leading edges of a turbine rotor blade.

Downstream of the cascade assembly there were sampling probes for

(a) alkalis, SO_2, SO_3 and HCl,
(b) NO_x
(c) exhaust dust, and
(d) gas analysis.

The gases were then quenched, by spraying water into the duct, passed through a venturi scrubber to wet the particles of dust before passing through a hydrocyclone which removed the wetted particles and water droplets from the gases. The cleaned gases finally passed through the pressure let-down valve before being exhausted to atmosphere via a chimney stack.

1.2 Air supplies

Air from three compressors of total nominal output of 2.3 lb/s at 7.8 atm pressure, was passed through filters and active carbon beds to remove water droplets and traces of hydrocarbons before flowing through air receivers to the main air orifice and main air control valve. The main air control valve was controlled from the control room by a Swartwout flow controller which received a signal from a pressure transmitter sensing the main air differential pressure. The air stream then split into two to supply (a) the air preheat tubes and (b) the corrosion tube assemblies. The supply to the air preheat tubes sub-divided into six flow streams, each having an orifice section, flow control valve and an isolating valve external to the pressure shell. All these flow control valves were controlled from the control room in a similar manner to the main air valve. The air supply to the corrosion tube assemblies divided into four streams which were also equipped with orifice metering sections, flow control valves and isolating valves. Flow through the corrosion tubes was governed by Foster indicator/controllers which sensed a metal temperature in the corrosion tube specimen assembly (see Fig. 2.6) and compared this with a preset temperature to give a "reduce flow" or an "increase flow" signal to its control valve. To avoid continual hunting, the metal temperatures were sensed for 7 s in a 100 s cycle, the control valve remaining at constant opening for the remainder of the cycle. Two further corrosion tube assemblies were not supplied with air and the metal specimens involved were thus maintained at bed temperature throughout the test series. Air from the outlets of the air preheat tubes and the corrosion tube assemblies was piped to the plenum chamber beneath the distributor plate

Air from the main air receivers was supplied to the top and bottom of the pressure shell via an orifice meter and remotely controlled valve to maintain the required static pressure in the shell. A pneumatically-controlled valve in a 4 in B.S.P. vent from the upper dome of the pressure shell was operated by a pilot valve, Swartwout differential pressure controller and differential pressure transducer to control the differential pressure between the plenum chamber and the space around the combustion vessel. The vent discharged into the hydroclone entry, i.e. upstream of the pressure let down valve.

Air from the receivers was supplied via a silica gel dryer of 20 ft^3/min capacity to two instrument air receivers, a low pressure receiver operating at 3.4 atm and a high pressure receiver operated at line pressure. The instrument air was used for operating the numerous remotely-controlled valves on the plant.

A further supply of dry air of approximately 0.4 lb/s at 7 atm pressure was available for use in the coal transfer and coal feeding sections of the plant.

1.3 Nitrogen

Nitrogen from a 53,000 ft^3 evaporator was available at pressures up to 10 atm for:

a. purging the plant,
b. use when required in the coal feeding and pressurising system,
c. as an inert atmosphere in the coal storage bunkers,
d. supply to the dip-leg "air slide", and
e. purging pressure tappings.

1.4 Steam

Approximately 2750 lb/h of steam at 8 atm pressure was supplied by a Stone-Vapour package boiler to three of the bed cooling tubes to heat the bed to about 300°F during the initial stages of start-up. After passing through throttling valves, external to the pressure shell, the waste steam from the circuits was condensed in a vertical pipe fitted with a water spray; the condensate was then run to waste.

1.5 Coal and acceptor preparation

Coal and acceptor were mixed before feeding to the combustor. The flow sheet for the preparation process is shown in Fig. 2.7. The raw coal was discharged from the base of the main coal storage bunker onto a vibratory gyrating screen having two screen decks of 1/16 in and 72 B.S. mesh respectively. The 72 B.S. mesh screen was deliberately run in a flooded condition so that the intermediate product contained some -72 mesh material. The nominal 1/16 in x 72 mesh output was blended with dolomite and stored in Storage Bunker I. The undersize material from the 72 mesh screen was rejected, and the oversize (+1/16 in) material was dried and milled. The mill incorporated a crude classifier which recycled most of the +1/16 in material. The mill product was discharged onto a vibratory gyrating screen having two screen decks of 1/16 in and 72 mesh. Oversize and undersize material were rejected and the main output was blended with dolomite and stored in Storage Bunker II. The discharges from Storage Bunkers I and II were mixed and conveyed to the coal feeding system. At this stage the product was 100% less than 1/16 in and about 15% less than 75 μm. This is typical of the size distribution which would be produced in a commercial plant.

The complex coal handling system was adopted for two main reasons: (a) initial separation of +1/16 in and -1/16 in was carried out to minimise the production of fines in the milling system; (b) subsequent blending of screened and milled coal was carried out because the ash characteristics (particularly ash content and ash degradability index) of each stream were different.

The raw dolomite was dried in a gas oven at 220°F before being screened on the vibratory gyrating screen fitted with 1/16 in and 72 B.S. mesh (operated in the "flooded" state) sieves. Oversize and undersize material was rejected.

The coal and dolomite were blended by sprinkling the prepared dolomite into the stream of sized coal as it left the vibration screen. The quantity of dolomite added was in accordance with the Ca/S mol ratio required. The rate of production of the blend was monitored continuously from the weight in the storage bunker.

1.6 Coal feeding

A flow diagram of the coal feeding system is given in Fig. 2.8, and a section through the Petrocarb feed vessel revealing the six internal feed cones is shown in Fig. 2.9. The storage and feed vessels were mounted on load cells and had capacities of 8500 and 6500 lb respectively. To ensure consistent output rates, the contents of the feed vessel were normally not allowed to fall below 3250 lb. Four of the coal outlets were connected by ½ in B.S. piping, each approximately 100 ft long, to the four coal nozzles: the remaining two outlets were each arranged as spare feed lines to two of the coal nozzles. Remotely-controlled valves in the coal feed pipes at the pressure shell could be operated from the coal feed station, and these allowed instantaneous selection of normal or spare feed pipes. In addition, the spare lines could be used as nitrogen or air supplies to "back-blow" the normal lines, after isolation from the combustor, for clearance of coal blockages.

Control over coal feed rate was obtained by adjusting the pressure differential between the coal feeder and the combustor. Minor changes to equalize flow in individual lines could be made by adjusting the quantity of conveying air (or nitrogen) admitted via Rotameters to the lines at the feeder end.

Two of the feed lines were equipped with a sampling device "teed" into them via an isolating cock. The samplers consisted of a small pressure vessel containing a cylindrical screen to support a disposable paper sample bag (from a domestic vacuum cleaner), together with an air vent.

1.7 Cooling and quench water

Cooling water for the tubes in the bed and freeboard was obtained from the mains water supply and boosted to 120 lb/in^2 gauge by a centrifugal pump of 7,000 gal/h capacity, driven by a 35 hp electric motor. The outlets of the cooling circuits discharged through manually-operated control valves sited at the inlets of Rotameters so that these operated substantially at atmospheric pressure: the Rotameters discharged into a tank which overflowed to the drains. The pump also supplied liner cooling coils fitted to the inside surface of the pressure shell and three sets of sprays for cooling the combustion products, viz:

a. 4 sprays at the entry to the quench section, 100 gal/h approx.,

b. 4 sprays at the discharge end of the quench section, 150 gal/h approx., and

c. 4 sprays in the throat of the venturi scrubber, 900 gal/h approx.

Provision was made to supply the following auxiliary circuits, as required, from the booster pump or directly from the mains water supply:-

a. the cooled shrouds surrounding the four coal nozzles,

b. the 2 U V flame failure detectors for the flame from the gas burner in the plenum chamber,

c. two sets of cooling tubes attached to the beam within the pressure shell from which the combustion vessel was suspended,

d. two heat transfer loops in the combustor at the surface of the bed, and

e. the cooling loops for the radioactive source and two Geiger tubes used for detection of bed level.

In the event of pump failure, water at 60 lb/in^2 gauge was available directly from the mains supply via a non-return valve. Although water, at this pressure would have been reasonably satisfactory for the cooling circuits, flow through the quench sprays would have been barely adequate.

1.8 Effluent disposal

Water containing finely-divided solids, removed from the combustion products by the hydroclone, flowed under the action of gravity into the sludge vessel, a horizontal pressure vessel approximately 7 ft long by 4 ft diameter. The level of liquid in this vessel was detected by a float switch, which under high level conditions supplied a signal to a pneumatically-operated discharge valve in the base of the sludge vessel. When the level in the vessel fell 1½ in to the low-level condition, the discharge valve closed. The operating pressure within the vessel was adequate to force the liquid effluent along a 2 in diameter pipe into a separating tank sited outside the building. Liquid from this tank overflowed into a header tank supplying a "dirty water" pump which transferred the effluent to a 50,000 gal reservoir where the solids settled out. Clear water from the reservoir was later discharged to the local sewers.

products, at the entry to the quench section adjacent to the water sprays, to increase the pH of the liquid effluents to 7. Liquid ammonia was obtained from cylinders and supplied via a variable area meter, non-return valve, control and isolating valves. The ammonia flashed off to a gas as it passed the final constriction in the piping and then rapidly dissolved in the water droplets in the quench section. In practice the flow of ammonia was manually controlled according to the colour developed by wide-range pH indicator paper which had been dipped into a sample of water discharged from the sludge vessel.

1.9 Gas

Gas for the plenum chamber burners was obtained from the mains, compressed to 4.7 atm approx. by a piston-type compressure of 1000 ft^3/h capacity before being delivered to the metering system for the burners. The burner assembly consisted of a line of five identical burners, of which the centre burner was a pilot. Operation of the system was controlled by a Honeywell flame-failure instrument in the following manner. When the ignition button was pressed, gas was allowed to pass through the pilot and an ignition coil was energised to provide a spark adjacent to the pilot. The flame from the pilot burner was sensed by a U V detector which then completed the electrical circuit to a solenoid valve in the gas supply to the four main burners. The detector and spark ignition units were duplicated so that an alternative could be selected in the event of non-ignition due to faults in the units or their wiring, and to obviate the necessity for gaining access to the inside of the pressure shell to cure the fault.

1.10 Dust Removal and Sampling

Dust from the primary cyclone blowdown was piped through the lower closure plate of the combustor pressure shell into a venturi scrubber where the particles were wetted with water from sprays. The dust/water mixture was passed to a disposal container through a [illegible] in bore boron carbide nozzle (see Fig. 2.10) to control the rate of blowdown. The amount of water used on the venturi scrubber sprays also had some influence on blowdown rate. For 3 minutes in every hour, the gases were diverted from the scrubber into a sample pot, 13 in long by 6 in diameter capable of withstanding the combustor test pressure. A filter in the outlet end of the pot retained the solids, whilst the cleaned gases were discharged through a silencer and steel orifice to atmosphere. The bore of this orifice was selected so as to be able to maintain the same mass flow of gases through the sampling system as through the venturi scrubber. Provision was made to bypass the scrubber and sample pot in the event of blockage in the scrubber. All valves used in the system were water-cooled plug or ball cocks.

Dust from the secondary cyclone blowdown was piped through two sample pots, 21 in long by 4 in diameter, fitted with filter elements in their discharge flanges. After one sample pot had been in service for an hour, the stream was diverted to the second pot for the following hour. A steel orifice at the outlets of the pots controlled the rate of blowdown from the cyclone: the cleaned gases were vented to atmosphere via a silencer. As in the primary blowdown system, a bypass was available for emergency use and all the cocks were water-cooled.

A half-area flow-mixer baffle was fitted (see Fig. 2.2) in the flange immediately downstream of the cascade blading. Exhaust gas sampling for dust content was achieved via a probe inserted on the axis of the quench chamber and terminating in a sharp-edged nozzle positioned upstream of the water sprays. The combustion products were sampled isokinetically, by the standard BCURA method, to collect gas-borne solids. Sampling was carried out over ten minute periods at approximately hourly intervals.

1.11 Bed Removal

Excess bed material was removed at intervals via a 2 in o.d. x 16 SWG Nimonic 75 tubular overflow pipe inserted at 40° to the vertical through one of the 4 ft wide side walls of the combustor, terminating 34 in above the distributor and 3½ in from the inside face of the combustor wall. External to the combustor, the overflow pipe was run vertically downwards through the lower closure plate of the pressure shell. Bed material was conveyed in combustion products down the overflow pipe, passed into a horizontal stainless steel side arm, ¾ in bore, 6 ft long, fitted with water-cooled isolating cocks, and finally discharged at atmospheric pressure into an open container placed on platform scales.

An extension which was originally fitted to the overflow pipe inside the combustor, became dislodged during Test Series 2 and was not re-fitted for subsequent test series. This extension had a ¾ in high x 1¼ in wide rectangular slot, positioned at 43 in above the distributor plate.

1.12 Temperature measurement

The location of the 101 thermocouples in the pressure shell is given in Table 2.2 and more detailed information on the position of the thermocouples in the bed and freeboard is available in Table 2.3. One of the two thermocouples at the cascade inlet was a suction thermocouple which was operated at spasmodic intervals throughout the test series to obtain the true total temperature of the combustion products. All the remaining static thermocouples were formed from Chromel/Alumel wires sealed into closed Pyrotenax sheaths; those in the corrosion tube assembly specimens were 0.041 in diameter, whilst the remainder were 0.125 in diameter.

1.13 Pressure measurement

Static and differential pressures throughout the plant were displayed on Bourdon tube type gauges and on mercury manometers respectively; they were also sensed by pressure transducers for output to the data logger and for control purposes.

Because the gases in the plenum chamber were essentially free from solid particles, the pressure points in the plenum chamber were regarded as the main pressure tappings and all differential pressures were referred to them. The other limbs of the differential pressure gauges were connected to pressure tappings in the freeboard, at the entries to the primary cyclone, the secondary cyclone, cascade and, venturi scrubber: these tappings were typically ⅛ inch diameter square-edged holes which were continuously purged with approximately 10 S.C.F.H. of nitrogen. Mercury catchpots, isolating cocks and bypass cocks were provided at the manometers used for measuring differential pressure.

1.14 Gas sampling and measurement

For normal monitoring of the combustion process, gaseous products were sampled simultaneously from three locations in the plant, viz:

a. top closure plate of combustion vessel;
b. at inlet to quench section; and
c. from the space at the top of the pressure shell.

All three sampling systems operated under positive pressure and consisted of a glass wool filter immediately external to the pressure shell, a self-draining stainless steel line to a cooler and catch-pot, a secondary cooler, calcium chloride and silica gel dryers and finally a blow-off bubbler. The gas supplies to the various gas analysis instruments were teed off immediately after the dryers. A valved vent to atmosphere from the outlet of the first cooler in the line allowed gas flow through the bubbler to be controlled.

The response times (the time to reach 95% of a new level following a step change) for the lines varied between 15 and 35 seconds according to combustor operating pressure and blow-off rate from the coolers. The various analysers (paramagnetic for oxygen, and infra-red absorption for carbon dioxide and carbon monoxide) had similar response times, viz: 15 to 25 seconds.

Except on a few rare occasions, the inlet quench section sampling point was used continuously throughout the tests as the main source of gas for the oxygen, carbon dioxide and carbon monoxide analysers. The output from these analysers was displayed in the main control room and at the fuel feeding position in addition to being recorded by the data logger for subsequent calculations. At this sampling point mixing could be considered complete.

Gases from the top plate probe were also simultaneously analysed for oxygen, carbon dioxide and carbon monoxide; the readings were displayed on charts. Gas composition at this point fluctuated more rapidly than the gases from the inlet quench section because mixing was not complete. Nevertheless, the reduced response time obtained with this line, particularly during start-up, made it an asset especially when temporarily operating under reducing conditions.

It was desirable that the pressure differential across the combustor walls was sufficiently high to prevent out-leakage of combustion products. The space above the combustor was therefore continuously monitored for traces of carbon dioxide by a sensitive infra-red analyser capable of indicating changes as small as 0.01%.

The Hartmann Braun infra-red SO_2 analyser was not available until Test Series 3, when it was installed in the gas sampling bay and supplied with combustion products from the inlet quench section probe. Thirty five hours after the start of Test Series 4 it was moved to the combustor platform and was supplied with gases from the alkali sampling probe immediately downstream of the cascade assembly. This arrangement enabled an extremely short line to be used which eliminated any possibility of condensation occurring in the pipe to the instrument.

During Test Series 1 gases for determination of nitrogen oxides content were sampled through a plain ¼ in diameter probe in the measuring section mid-way between the cascade and quench sections. Analysis was made in two places, (a) adjacent to the pressure shell and (b) approximately 20 ft from the pressure shell. In both locations, gases were blown off to the atmosphere to sweep the line, and a small bleed of gas was passed to the analyser. During the remainder of the test series the plain probe was replaced by a water-washed probe, the spray head passing 20 to 50 gal/h of water. A new self-draining sampling line, 40 ft long x ¼ in o.d. stainless steel pipe, was installed for Test Series 2, and terminated in a catch pot vented to atmosphere via a constant area flowmeter.

1.15 Bed level measurement

Three methods of estimating depth of bed in the combustor were available. These were:-

(a) by pressure differential;
(b) by heat transfer measurement, and
(c) by absorption of gamma radiation.

(a) Pressure tappings were provided on one of the 2 ft wide side walls of the combustor at 9¾ in 27¾ in and 98 in above the distributor plate. All three tappings were continuously purged by nitrogen; the two lower tappings were in the bed and the highest tapping was in the freeboard. Assuming that the bulk density of the solids comprising the bed did not vary with bed height and that the pressure differential in the freeboard between the surface of the bed and the upper pressure tapping was constant, the differential pressures afford an estimate of bed depth and bed bulk density, viz:

if differential pressure between 9¾ in and 27¾ in tappings = P_1

differential pressure between 9¾ in and 98 in tappings = P_2

and P_1 and P_2 are measured in inches of mercury.

$$\text{bed depth} = \left[\frac{18\ P_2}{P_1} + 9\tfrac{3}{4}\right] \text{ in}$$

bed bulk density = $47P_1$ lb/ft^3.

(b) For estimating bed height by heat transfer measurement, two horizontal hair-pin tubes, each fabricated from 3 ft lengths of ⅜ in o.d. En 58b tubing and having surface areas of 42 in^2 were fitted through one of the 2 ft wide sides of the combustor at 36 in and 45 in above the distributor plate. A cooling water flow was passed first through the lower loop and then through the upper loop, its temperature rise being obtained from thermocouples installed at the inlet of the lower hair pin and the inlet and outlet of the upper hairpin. A higher temperature differential was obtained when a loop was immersed in the bed than when the loop was in the freeboard.

(c) The third method of estimating bed height utilised a 400 mC Caesium source held in a water-cooled casing fixed on the outside of a 4 ft side of the combustor at 44 in above distributor plate level. The outputs from two Geiger tubes, mounted on the outside of the opposite combustor wall at 37 in and 46 in height above the distributor plate, were displayed by ratemeter indicators in the control room. A fall in bed level below the plane of the source unit and Geiger tube resulted in an increased count being obtained.

All three methods were used in the test series, but method (a) was found to be most informative in that a rate of change of bed depth could be obtained. This method was used to indicate when it was necessary to remove bed material to maintain a desired bed level.

The electrical outputs from much of the instrumentation e.g. thermocouples, static and differential pressure transmitters, load cells, and gas analysers, was recorded on punched tape at ten minute intervals by a data logger having 197 channels, in addition to being displayed at the various control positions.

2. GENERAL OPERATING PROCEDURES

2.1 Preparation

Before the start-up operation commenced, approximately 1800 lb of Newdigate shale was loaded into the combustor to form the initial bed. The coal feeding unit, the combustor and effluent disposal units were pressure tested to 7.5 atm prior to elimination of minor leaks at 6.5 atm pressure.

2.2 Warming up

Steam at 8 atm pressure was then passed through three of the bed cooling coils and the bed fluidised at about 1.5 ft/s with cold air. This air flow pressurised the combustor to 1.5 atm abs approx. After about one hour, when the warm air from the bed had heated the internal surfaces of the cyclones and their blowdown legs to above the water dewpoint, the gas burner in the plenum chamber was lit. In earlier combustor tests, when the bed was not preheated prior to lighting the gas burner, condensation occurred in the dust extraction system so that fines elutriated from the bed choked the cyclone blowdown legs. The gas input was regulated to obtain a maximum air temperature below the distributor of 1400°F. As the bed warmed up the mass flow of air was decreased to maintain fluidising velocity in the range 1.5 to 1.8 ft/s. The quench section and venturi scrubber water sprays were established when the inlet cascade temperature reached 180°F.

2.3 Start up

When the temperature throughout the bed reached 930°F conveying air was admitted via the four coal nozzles, the combustor pressure was set to 2 atm and a small flow of coal was fed to the bed. Providing the carbon monoxide content of the combustion products did not peak to more than 1.5%, coal input rate was gradually increased and air flow adjusted to obtain a progressive rise in bed temperature with fluidising velocity in the range 1.8 to 2.0 ft/s. The coal flow was either reduced or stopped altogether if the carbon monoxide content became excessive. Water flow was set to one of the freeboard gas cooling coils if the freeboard gas temperature exceeded bed temperature. Gas flow to the plenum chamber burner was reduced to

1 therm/h when the bed temperature reached 1200°F and shut off at a bed temperature of 1380 - 1430°F. Once the bed temperature exceeded 1300°F, the carbon monoxide content of the combustion products usually dropped slowly to the normal operating level of 0.1% or less.

2.4 Increasing Pressure

When bed temperature reached 1470°F, bed cooling circuits were commissioned as necessary whilst air flow and operating pressure were increased until the set running conditions were obtained. During the short periods when a bed cooling circuit was brought into (or out of) service, very rapid changes in metal temperature occurred. A water-air emulsion was supplied to several of the circuits during this period to prolong the life of the tubes. Until the combustor operating pressure exceeded 2.7 atm, the liquid effluent from the hydroclone was allowed to drain to the sewers. At higher pressures, the effluent was diverted to the dirty water treatment system.

As operating pressure was increased, flow through the primary and secondary ash blow-down systems was reduced by shutting off the emergency bypasses and duplicate orifice assemblies which had been in circuit during start-up. Flow through the two systems was then controlled by the resistance of a single orifice at the discharge points. Water flow was established as soon as possible to the horizontal venturi scrubber in the primary cyclone blowdown piping. An increase in the amount of spray water resulted in a decrease in gas flow; water flow was adjusted to obtain a metal temperature of 550° to 750°F up-stream of the venturi scrubber where the piping passed through the closure plate. The corresponding metal temperature for the secondary cyclone blowdown system was 300° to 350°F. If this was not obtained during steady operation with the normal discharge orifice, the possibility of blockage of the filter in the outlet of the sample pot was investigated.

2.5 At steady conditions

As soon as the set conditions for the test had been attained (normally 1½ to 3 hours from coal on), the data logger was switched on to operate on a ten minute cycle.

No chart records were available for the thermocouples during the logging period as their electrical outputs were automatically switched to the data logger input a few seconds before the commencement of the period. The speed of reading the data was limited by the speed of the paper punch to about 2 channels per second.

Approximately 1 lb/h of liquid ammonia was bled in the inlet to the quench section to neutralise the acids formed by absorption from the combustion products. Samples of the liquid effluent were taken every hour and checked with pH indicator paper. The ammonia flow was then regulated as necessary to obtain an effluent having a pH of 7.

Primary cyclone fines were sampled every hour by the two following procedures. First, the wetted fines discharged from the venturi scrubber were diverted to a 40 gallon drum for ten minutes. Each drum accumulated three hourly samples before being changed. After the test series, when the fines had settled to the bottom of the drum, the sludge was dried in a gas oven and weighed to give an estimate of mass flow of fines during the period. Second, the blowdown was diverted, from a point upstream of the venturi scrubber, into a sample pot for a three minute period. These samples were batched as necessary and submitted for chemical and physical analysis: their weights provided a check on the estimates of mass flow obtained from the wet sampling system.

Secondary cyclone fines were sampled continuously by passing the blowdown through a sample pot; the sample pot was changed every hour. These samples were weighed to obtain the hourly estimates of mass flow and after batching as required were submitted for chemical and physical analysis.

Estimates of dust loading in the combustion products were made at approximately hourly intervals and with a sampling period of ten minutes. There were periods during some of the tests when the intervals between dust samples was longer than this due to the operators being involved with less frequent sampling routines or with servicing the probe and sampling equipment.

Combustion products were sampled for ten minute periods every 1 to 1½ hours from the probe fitted to the duct immediately downstream of the cascade section, and analysed for sulphur dioxide and sulphur trioxide by the modified Shell chemical method[2]. During periods when it was known that the level of these components would be changing rapidly, the frequency of sampling was increased to one determination every twenty minutes.

Alkali determinations were made relatively infrequently, i.e. once per twelve hour shift. Gases were sampled over a twenty minute period, from the probe immediately downstream of the cascade and alkali content estimated using Ounsted's electrostatic precipitator method[3] and subsequent determination of sodium and potassium with a flame photometer.

A 2 lb sample of the coal plus acceptor fed to the combustor was taken every three hours. The coal sampler was teed into the supply line to one of the coal nozzles at a point directly beneath one of the coal feeder discharge cones. In order to sample the whole stream of solids, the following procedure was adopted. The cock in the coal supply line to the nozzle was shut and after the line had been blown clear by the conveying air, the coal flow was supplied to the combustor via the spare line. The arrangement of cocks allowed the conveying line to be isolated and the sampler to be connected directly to the coal feeder outlet so that coal fell vertically downwards into the sampler aided both by gravity and by the flow of air from the feeder. After closing the cock at the inlet to the sampler, feeding via the spare line was discontinued and the conveying line cock on the normal feed line was opened to re-establish coal supply to the coal nozzle. The sampler was then dismantled, the solids emptied into a screwed-cap jar which was sealed and stored for batching, as required, with other samples.

The frequency of removing bed material from the combustor was dependant upon the nature of the ash in the coal and the size grading and proportion of acceptor fired with the coal. Typically, 150 lb of material representing 4 inches of bed was removed on each occasion: the minimum time between extractions was of the order of two hours. The removal procedure consisted solely of opening the cock in the weir blowdown pipe external to the pressure shell and tapping the piping at the change in direction beneath the combustor. This allowed the settled solids remaining in the pipe from the previous extraction to be swept out in the stream of solids plus combustion products. The solids flowed out of the open end of the weir blowdown piping into a tared container; no control over flow rate was provided. When sufficient material had been removed from the bed, the cock in the blowdown piping was closed.

On the rare occasions during the tests when the bed continuously lost height, it was necessary to add additional inert material. The procedure used to do this was to discontinue the normal flow of coal to one of the four nozzles and to feed instead a mixture of 80% w/w inert material + 20% w/w coal from a small fluidised feeder of 800 lb capacity, operated at a positive differential pressure with respect to the combustor. The inert material used was either shale or bed material recovered from earlier non-acceptor test runs. Feed rate was matched to maintain bed temperature at 1470°F and thus represented a higher coal input than normal since it was necessary to supply additional heat to raise the cold inert solids to the bed temperature.

2.6 Shut down

The shut-down procedure was straightforward comprising the following main actions:-

(a) turning off coal by closing the discharge cocks beneath the feeder. A flow of conveying air was maintained through the coal nozzles to purge the lines.

(b) as the bed cooled, reducing combustor pressure in 5 lb/in^2 steps to maintain 2 ft/s fluidising velocity.

(c) shutting off the water supply to the bed and freeboard cooling circuits.

(d) diverting the liquid effluent to the sewers.

(e) when bed temperature fell to 750°F, shutting off the water supply to the venturi scrubber and opening the bypass systems in the primary and secondary cyclone blow-down systems.

(f) when bed temperature fell to 550°F, shutting off the combustor fluidising air supply and the water flow to the coal nozzle cooling jackets.

(g) immediately after stage (f), shutting off the water supplies to the quench section sprays and the venturi scrubber.

2.7 Emergency shut-down in event of failure of public electricity supply:

Failure of the mains electricity supply would result in failure of the majority of the automatic controllers, two out of the three air compressors, and all temperature indicating/recording instruments, gas analysers and the inter-comm system. Although the main air valve would fail safe in the closed position a limit stop was provided to enable a small flow of air to be fed to the combustor for purging purposes: the air supply to the space between the pressure shell and the combustor would however cease, causing an imbalance of the two pressures. The pump supplying high pressure water to the quench section sprays and to the cooling circuits would stop, but the circuits would immediately by supplied with water from the normal mains, albeit at a greatly reduced pressure.

The following procedure was successfully adopted to avoid damage to the plant when the mains electricity supplies failed:-

(a) The building was evacuated except for two control room staff.

(b) Coal flows to the combustor were shut off at the feeder isolating cocks and also by use of a control room lock out switch.

(c) The control valve in the pressure balance piping, linking the combustor outlet piping with the space between the combustor and pressure shell, was fully opened, (although this valve was pneumatically controlled, its maximum opening under auto conditions was much less than its maximum possible opening).

(d) Corrosion tube air supplies were shut off when the combustor pressure fell to 1.7 atm.

(e) The ammonia supply to the quench system was stopped and water to the venturi scrubber in the primary cyclone blowdown system was turned off.

(f) The quench section water sprays were then shut off and immediately after this had been done, the manual cocks in the air supplies to the air preheat tubes were closed.

(g) Finally the emergency bypasses in the primary and secondary cyclone blowdowns were opened.

2.8 Mass Balances

Mass balances were computed for each of the Tests, using the following general procedures:-

2.8.1 Weights and Flow Rates

The weight of the bed was calculated from the static pressure-drop across the bed, and the rate of material "gained by bed" was the gain in bed weight during the test divided by the duration of the test.

Coal and Acceptor: The individual feed rates of coal and acceptor were obtained from the flow rate of mixture and from the value of d, the weight fraction of acceptor in the mixture, calculated from the equation:

$$d = (x - cy)/(C(1 + c) - c)$$

where x and y are respectively the weight fractions of CO_2 and "ash" in the mixture, c is the CO_2/ash ratio in the raw coal, assumed to be constant, and C is the CO_2 content of the raw acceptor. These assumptions eliminate the need to assume a constant composition for the raw coal.

Air and Nitrogen: These gases were measured as described elsewhere in this Appendix. The coal conveying air was the total air used for fluidising the feed vessel and for conveying, less the vent flow from the feed vessel.

Weir Solids: The flow rate of weir solids was the actual weight of material extracted over the weir during the test, divided by the duration of the test. The rate of material gained by bed should be added to the flow rate of weir solids to obtain the flow rate obtainable under steady-state conditions.

Cyclone Solids: The primary cyclone solids flow rates were those assessed by the wet sampling method.

Exhaust Dust: The flow rate of dust escaping with flue gas exhausted from the secondary cyclone was assessed from the weight of dust present in a known weight (usually approx. 40 lb/h) of flue gas sampled for 10 minutes.

Flue Gas: The flow rate of flue gas was calculated assuming a total materials balance, and the water vapour content of the flue gas was calculated assuming a hydrogen balance.

2.8.2 Components of Materials

Ash: The "ash" contents of coal-acceptor mixtures were obtained by the usual method for determining the ash content of coal. Analysis of the "ash" from these mixtures invariably showed a high sulphate content, due to capture of sulphur by the calcined acceptor present, and the "ash" contents have therefore been corrected to the sulphate-free basis. "Ash" contents of acceptor, bed materials and output solids were not determined, and in all cases were assumed to be equal to:

$$(100 - \%\ H_2O - \%\ SO_3 - \%\ CO_2 - \text{Elemental carbon})\ \%$$

Carbon: It was assumed that air contains 0.03 mol % of CO_2.

Hydrogen: Hydrogen inputs in coal and acceptor include hydrogen present as moisture. The moisture content of the main combustion air was assumed to be that corresponding with saturation under the conditions at which the flow was measured. The coal conveying air was dried by silica gel, and the nitrogen input was assumed to be dry. Hydrogen detected occasionally in output solids was assumed to be present as moisture absorbed after weighing. In no instance was hydrogen or methane detected in the flue gas, and the total hydrogen input was therefore assumed to be converted to water vapour in the flue gas.

Nitrogen: For the purposes of the mass balances, nitrogen oxides in the flue gas were assumed to be present as nitric oxide. The elemental nitrogen content of the flue gas was obtained by difference, and therefore includes analytical errors; it was assumed to have a molecular weight of 28.17, as for "nitrogen" in air.

Oxygen: The oxygen content of coal-acceptor mixture was, as usual, obtained by difference (after correcting the "ash" content for sulphate) and therefore includes analytical errors. The oxygen contents of acceptor, bed material and output solids comprised oxygen present as CO_2 and SO_3. The oxygen content of flue gas was the sum of oxygen present as CO_2, O_2, CO, NO, SO_2 and SO_3.

Sulphur: Sulphur in acceptor, bed materials and output solids was assumed to be present as sulphate.

Calcium, Magnesium, Sodium and Potassium: These elements were determined in input and output solids as their oxides, but the oxygen combined with them is not included in the oxygen inputs and outputs. Alkalis present in the flue gas were determined in the form of condensed aerosols, but were assumed to be present in the gas as vapours of the oxides.

Chlorine: Chlorine was assumed to be absent from acceptor. Chlorine in the flue gas was probably mainly in the form of HCl, but no allowance was made for the hydrogen associated with chlorine in gas when computing the vapour content.

3. RESULTS

3.0 Summary

The detailed results of each Test Series are presented in Section 3.1 to 3.5. The main variables investigated were Ca/S ratio, type of additive, size of additive and coal. Other operating variables such as fluidising velocity, bed depth and bed temperature were substantially constant at 1.9 ft/s, 3.75 ft and 1470°F, respectively. Operating pressure was either 3.5 or 5 atm absolute.

3.0.1 SO_2 emission:

All the data on the reduction in SO_2 emission are plotted in Fig. 3.12. The main conclusions, as far as Task II is concerned, are:

(1) Reduction was not affected by pressure in the range $3^1/2$ to 5 atm.

(2) Altering the median size of the additive (in this case dolomite 1337) from 1100 to 400 micron did not affect the reduction in SO_2 emission. The change in size was produced by widening the size distribution, i.e., by increasing the proportion of fines.

(3) Reduction with Welbeck/U.K. dolomite appeared to be slightly higher than with Pittsburg/Dolomite 1337, although the range of Ca/S ratios investigated did not overlap sufficiently for a firm conclusion to be drawn.

(4) Reductions obtained with limestone 18, although considerably lower than with dolomite (on a Ca/S basis), were surprisingly high in view of the fact that limestone does not calcine at these conditions.

The time taken to reach an equilibrium SO_2 emission was substantial when dolomite was the additive - about 20 to 50 hours when the initial bed contained no dolomite. The accumulation of unconverted CaO in the bed also reached a maximum in a similar time as illustrated in Fig. 3.5. With limestone 18, equilibrium was reached much more rapidly.

SO_2 emission appeared to fluctuate in sympathy with the coal feed rate. Figure 3.9 shows typical extracts from the recorded outputs of the O_2 and SO_2 gas analysers. The variations in O_2 content were due to fluctuations in coal feed rate.

3.0.2 NO$_X$ emission The NO$_X$ content of the exhaust gases was generally in the range 80 to 190 p.p.m. (v/v). None of the variables investigated appeared to have any effect on NO$_X$ emission.

3.0.3 Particulate emission The dust burden of the gases passing over the cascade was about 150 lb dust/10^6 lb gas (about 0.1 grains/sft^3) when burning Pittsburgh coal. This was about twice the dust loading obtained when burning Welbeck coal. The inert input (dolomite or limestone) was considerably higher with Pittsburgh coal, partly because of its higher S content, and partly because it was decided to use higher Ca/S ratios with the Pittsburgh coal.

The dust was sized by Coulter Counter and found generally to have a median size of 6 to 8 micron with about 90% less than 30 micron. As with all determinations of size distribution in this range, however, the value of the data, is open to question. Earlier tests with Welbeck coal had shown that most of the larger dust particles were in the shape of 'platelets' which would not be regarded as erosive.

3.0.4 Combustion efficiency In the later tests with Pittsburgh coal the combustion efficiency was greater than 99%. In the early tests, when the acceptor was Dolomite 1337 with the high median size, the efficiency was about 97½%. This lower efficiency was probably due to the poorer mixing in the coarser bed produced by using the coarser dolomite.

With Welbeck coal, under fluidising conditions similar to the later tests with Pittsburgh coal, the combustion efficiency was about 98%.

Combustion in the freeboard, based on heat balance between the top of the bed and the top of the freeboard, amounted to 2 to 3% of the coal heat input.

The major loss of combustion efficiency in all cases was in the carbon of size less than 50 micron elutriated from the bed.

3.0.5 Temperature distribution The temperature of the bed showed a small, but consistent, rise of 30 to 40°F between a level near the bottom of the bed and one near the top. At any particular level the variation in temperature was about ± 20°F, although no measurements near a coal feed point were made.

3.0.6 Blade cascade and target rods The blades were not cleaned between tests and the appearance did not vary greatly from test to test. Typical appearances after Tests 2 and 3 are shown in Fig. 3.11. Usually there was a light accumulation of dust on the leading edge with flecks of dust adhering to the concave faces and negligible deposition on the convex faces. There were no signs of sintered deposits or of erosion.

The target rods usually had a small knife-edge of deposit on their leading face, and had developed a considerable 'tail'. Cross-sectioning and examination under a microscope revealed no evidence of corrosion or erosion.

3.1 Test Series 1

3.1.1 Objectives of Test Series

To measure the emission of SO_2 and NO_X from the combustor when burning Welbeck coal and U.K. dolomite at nominal Ca/S ratios of 0, 1 and 2.

3.1.2 General description of Test Series

3.1.2.1 Outline of Test Series

The test was carried out between 1st and 5th June 1970 and lasted for 100 hours. The test was carried out in three main sections: an initial period of 8 hours with no dolomite addition, followed by two periods of 47½ and 44½ hours each at a different level of dolomite addition. The test was limited intentionally to one operating pressure so that accurate information could be obtained on the time required to reach equilibrium.

Based on the measurements made, five Test periods were selected for carrying out heat and mass balance computations. Coal, primary and secondary dusts were bulked according to each test period. Operating conditions are given in Table 3.1 and analyses of coal, dolomite, cyclone, exhaust dust and bed samples are given in Tables 3.2 to 3.10.

Average gas composition measurements for each of the Test periods are given in Table 3.11. Combustion conditions were substantially constant throughout the test, as shown in Table 3.12, where the variations of bed temperature and gas composition are illustrated.

After the test, two of the water circuits were found to be leaking slightly.

3.1.2.2 Coal and dolomite preparation

For this test the coal was not screened before milling (i.e. all the raw coal was milled). The dust caused during the coal/dolomite blending process was controlled by means of vacuum cleaners. After the test it was found that they had preferentially extracted dolomite dust from the blend. In consequence, the actual Ca/S ratios of the blends were lower than intended. For subsequent Test Series the extraction system was modified to avoid this problem.

3.1.2.3 Sulphur emission

Measurements of the SO_2 and SO_3 content of the flue gas were made at approximately hourly intervals (more frequently when the rate of dolomite injection was nominally increased) using the "Shell" condensation method[2] for SO_3 and the BCURA iodine absorption method[4] for the SO_2 content.

The results are given in Table 3.13 and in Fig. 3.1. Also shown in Fig. 3.1 are the variations in the approximate Ca/S stoichiometric ratio in the feed, calculated from the CO_2 contents of the coal/acceptor samples and an assumed average value for the sulphur and ash contents of the coal. The tabulated data under the various Test periods in Fig. 3.1 refer to the mean operating conditions for these periods and give the actual Ca/S mol ratios based on the Ca and S contents of the bulked coal/acceptor samples collected during that period.

Table 3.14 shows the percentage of sulphur retained in each of the test periods.

3.1.2.4 NO_x emissions

Determinations of oxides of nitrogen were made at irregular intervals throughout the test. Results are summarised in Table 3.15. When the two methods used (Saltzman[5] and Hersch)[6] were operated concurrently, reasonable agreement between the two estimates was obtained.

3.1.2.5 Retention of alkalis and chlorine

Determinations of sodium, potassium and chlorine in the flue gas are summarised in Table 3.15A. Table 3.14 also shows the percentages of Na_2O, K_2O and chlorine retained. Both these and the sulphur retention figures are expressed as 100 (weight of component input - weight in gas)/weight of component input. To avoid negative results, chlorine retentions are based on weights of chlorine in the output solids.

Alkali retention was virtually complete at all Ca/S mol ratios.

3.1.2.6 Mass balances

The mass balances computed for each of the test periods of Test Series 1 are presented in Tables 3.16 to 3.19A. The computations were based on the assumptions already described in Section 2.8, together with the additional assumptions listed underneath the tables.

With some exceptions, the balances are satisfactory. An obvious exception was the chlorine balance: in Tests 1.1 to 1.4 inclusive, the chlorine content of the flue gas exceeded the chlorine input in coal fed. This may have been due to errors of determining the chlorine content of the gas. The periods selected for the tests of the series corresponded with times when the sulphur emission appeared to have become constant following a change in the rate of acceptor input. However, it can be seen from the rates "gained by bed", and from analyses of bed materials at the start and end of each test, that the bed composition did not become constant during the Test Series. Comparison of coal ash and acceptor analyses suggests that until bed composition became constant, there would be gains in the sulphur, calcium and magnesium contents, and falls in ash and potassium contents during a test, and this behaviour was shown in each of the four tests following the start of acceptor feeding. It is likely that an appreciable error was associated with the method of determining bed weight. The rates "gained by bed" are based on differences between estimates of two large bed weights (approx. 1800 lb) and two analyses. They are therefore likely to be more in error than many of the other input and output rates and may account for most of the differences between inputs and outputs Analytical errors associated with analyses of "ash" in the coal-acceptor mixture and of acceptor can lead to errors in the rates of individual components of coal and of acceptor; this is revealed by the negative magnesium content of coal in Test 1.5. However, the sum of the inputs in coal and acceptor equals that computed from the analysis of the mixture.

3.1.2.7 Heat Balances

The heat balances are presented in Table 3.20. The heat balances are poor, since only 83 to 88% of the total heat input is accounted for. This could be due to the leakage of water into the combustor and the results are consistent with a leakage rate of 250-300 lb/h.

The data are expressed in million Btu/h, rounded off to the nearest 0.01 million Btu/h, and the calculations were based on the assumptions given below.

All heat quantities refer to a datum temperature of 32°F. The heat input in coal-acceptor mixture, which includes sensible heat of solids (approx. 0.002 million Btu/h), is predominantly the potential heat of the coal fed, based on its gross calorific value. Potential heats of output solids are calculated from their elemental carbon contents, assuming a heat of combustion of 14,544 Btu/lb carbon. The total heat of weir solids (sensible plus potential heats) includes the heat content of material gained by the bed. Sensible heats of outlet gases are based on the appropriate temperatures, i.e., bed temperature for weir gas blowdown, the relevant cyclone temperature for the cyclone gas blowdowns, and the secondary cyclone exhaust temperature for the exhaust flue gas. Potential heats of gas outputs are the heat of combustion of the CO in the gas, and the latent heats refer to the water vapour content. The heats of acceptor reactions:

$$CaCO_3 + SO_2 + \tfrac{1}{2}O_2 = CaSO_4 + CO_2 + 77.1 \text{ kcal/mole}$$
$$MgCO_3 = MgO + CO_2 - 24.2 \text{ kcal/mole}$$

were calculated from heats of formation of reactants and products given by O. Kubaschewski and E.Ll. Evans[7] ("Metallurgical Thermochemistry". London: Pergamon Press, 1958).

The main loss of potential heat (i.e. combustion efficiency) was in the carbon carried over into the primary cyclone. The bulk of this loss occurred in the finer fractions (less than 53 micron) as shown in Table 3.21.

3.1.2.8 Corrosion of metal specimens in the bed

The specimens were examined visually for deposits and corrosion or erosion damage. A few randomly-selected specimens were then sectioned, mounted and polished for metallographic examination, but the majority were descaled in a sodium hydride bath and the weight change for the run determined.

The high temperature tubes 1 and 6 (1450°F) had a matt red coloured film on the underside thinning to clean metal surfaces at the top of the tubes. This deposit was thin (.001") and had lifted in some places to expose clean metal beneath. Tube 2 (1320-1380°F) was similar but more patchy. Tubes 3 and 4 (1020-1160°F and 930-1020°F) were completely covered by a dark red to black film with a polished appearance. There was no indication of it breaking away from the surface. The 1% Cr ½% Mo and 2¼% Cr 1% Mo specimens in these tubes had a blistered appearance. Tube 5 (660-1020°F) had a dark brown polished film on the top surface similar to tubes 3 and 4. The underside, however, had a striated appearance because of the leakage of cooling air around the edges of the specimens, the leaks being caused by sagging of the tube assembly during the run.

The rates of weight loss of the specimens after descaling are given in Table 3.22 and are summarised in Table 3.23. The metallographic examination confirmed the weight loss results; no intergranular penetration was found in any of the specimens (see Table 3.24). The higher weight losses of the 2¼% Cr 1% Mo, 1% Cr ½% Mo ferritic specimens were associated with a general surface roughening.

3.1.2.9 Blade cascade and target rods

See Section 3.5.2.9 at end of Test Series 5.

3.2 Test Series 2

3.2.1 Objective of Test Series

To measure the emission of SO_2 and NO_X from the combustor when burning Pittsburgh coal with dolomite 1337 addition at a nominal Ca/S ratio of 2.

3.2.2 General description of Test Series

3.2.2.1 Outline of Test Series

The Test was carried out between 19th and 23rd October 1970 and lasted for 81½ hours. During the first 8 hours of the test considerable loss of bed material occured, and about 750 lb of make-up shale was added in this period. This coincided with a period when coal prepared from the -1/16 in fraction was being used. The ash from this fraction had an extremely low bulk density, and it is possible that all the input ash was being elutriated. Alternatively, material may have been carried up the dip-leg of the recirculation cyclone because the "airslide" settings at the base of the dip-leg were too high for the Pittsburgh coal/dolomite mixtures. After 8 hours operation the "airslide" flows were reduced, coincident with using a well-mixed blend of coal prepared from the +1/16 in and -1/16 in fractions. No further difficulties were experienced in maintaining bed level and bed material was removed at regular intervals.

After 73 hours operation the plant had to be shut down rapidly when the combustor pressure suddenly increased from 60 p.s.i.g. (5 atm) to 73 p.s.i.g. due to a failure of the pressure control system. The test was resumed after a delay of six hours for plant inspection.

After 81½ hours operation the Test was terminated when it became apparent from the temperature records that the bottom 6 inches of the bed had cooled down and defluidised. Subsequent examination of the combustor showed that sintered ash agglomerates had formed around and above the coal nozzles; the nozzles had also overheated. At the time it was assumed that the sinter was a result of the low ash-fusion temperature of the Pittsburgh coal and the immediate solution appeared to be to provide additional cooling at the coal nozzles so as to reduce the temperature in their immediate vicinity. Accordingly water-cooled jackets for the coal nozzles were fabricated and installed.

The test was restarted using the same bed material (after screening out the +1/16 in sintered lumps). It was noted during the warm-up period that the bed was more difficult to fluidise (requiring about twice the normal fluidising velocity at low bed temperatures) than usual, and after 4 hours operation on coal the lower part of the bed again defluidised. The plant was shut down immediately (on the previous occasion the bed was operated for the final 3 hours with the bed partially defluidised) and, on inspection, no evidence of sintering could be found. At this point it was decided to terminate Test Series 2.

Analysis of the bed material after the test showed that there had been a major change in size distribution since the beginning of Test Series 2, the median size of the particles increasing from about 400 micron at the beginning to about 900 micron at the end. This was due partly to the friable nature of the ash, but mainly to the lack of fine particles in the dolomite 1337. The dolomite was fed in the essentially "as received" state (after the small amount of +1/16 in material had been screened out) and had a median particle size of about 1000 micron (see Fig. 3.2.).

It is now believed that the difficulties experienced at the end of Test 2 were not caused by sintering, but were due to the alteration in the particle size of the bed. Fig. 3.3 shows the fluidising characteristics of the material before-and-after Test 2, as determined in a 12 in diameter vessel using cold air. Although the after-test material was more difficult to fluidise, it is not immediately obvious that the bed would defluidise under test conditions until it is remembered that if the temperature of the gases falls, the gas velocity will also fall correspondingly. An increase in the particle size of the bed material would reduce the circulation of heat to the bottom of the bed and it is likely that in a combustion system there is a threshold limit of gas velocity which is necessary to maintain the temperature of the bed. Below this limit the temperature, and therefore gas velocity, will fall and the bed will defluidise.

Four Test periods of steady operation and a fifth which included the defluidising period were selected for computation of combustion efficiency, heat and mass balances. Samples of coal, primary and secondary cyclone fines, exhaust dust and bed extract were bulked before analysis to conform with these selected periods. Operating conditions are given in Table 3.25 and the analysis of the coal, dolomite, cyclone, exhaust dust and bed samples are given in Tables 3.26 to 3.35. Average gas composition measurements for each of the Test periods are given in Table 3.36, variations in bed temperature and gas composition are given in Tables 2.37 and 3.38.

3.2.2.2 Sulphur emission

Measurements of SO_2 and SO_3 were made at approximately hourly intervals using the "Shell" condensation[2] and BCURA iodine absorption methods.[4]

Results are tabulated in Table 3.39 and Fig. 3.4. Also shown in Fig. 3.4 are the variations in the approximate Ca/S stoichiometric ratio in the feed, calculated from the CO_2 contents of the coal/acceptor samples and an assumed average value for the sulphur and ash contents of the coal. The tabulated data under the various test periods in Fig. 3.4 refer to mean operating conditions for these periods and give the actual Ca/S mol ratios based on the Ca and S contents of bulked coal/acceptor samples collected during that period.

Equilibrium as regards SO_2 emission appeared to be reached in 15 to 20 hours. This is considerably shorter than the 50 to 60 hours required in Test 1, presumably because in Test Series 2 the initial bed material contained some "free" calcium, the dolomite input rate was higher, and the dolomite size was such that more was likely to be retained in the bed. Support for this explanation is provided by Fig. 3.5 which shows the variation of weights of total and of unconverted calcium (expressed as lb of equivalent CaO) in the bed, and the concentration of SO_2 in the flue gas. The diagram has been simplified by linearly interpolating between weights of CaO at the times of withdrawal of bed material. During most of the test the average weight of unconverted CaO in the bed was approximately 300 lb, and this weight was reached after approximately 20 hours. Some of the variation in sulphur content of the gas was probably due to variation in the rate of sulphur input; for example, during Test 2.4 (4081 and 4352 min from start of test) the average rate of sulphur input was 20% higher than in Test 2.3 (2304 to 4031 min), but for the first 4000 min of the test the sulphur content of the gas reflects the free calcium inventory reasonably well. During the last 500 min of Test 2, the SO_2 levels started to increase as a consequence of the poor fluidisation and eventual sintering experienced in this test. The percentage of sulphur retained in each of the test periods is shown in Table 3.40.

3.2.2.3 NO_x emissions

Determinations of oxides of nitrogen in the exhaust gases were made throughout the test, mainly using the Hersch[6] method. Results are summarised in Table 3.41. For this and subsequent tests, a water-washed probe was used.

3.2.2.4 Retention of alkalis and chlorine

Determinations of contents of sodium and potassium oxides and chlorine in the flue gas were made during Test Series 2 and are summarised in Table 3.42. The percentage retentions of alkalis and chlorine are shown in Table 3.40. As in Test 1 the retention of alkali was virtually complete. It is thought that the figures for the retention of chlorine obtained in Test Series 2 are more reliable than those for Test Series 1; the percentage retentions are higher but this may be due to the lower chlorine content of the coal.

3.2.2.5 Mass Balances

The mass balances computed for each of the tests of Test Series 2 are presented in Tables 3.43 to 3.47. The computations were based on the assumptions already fully described in Section 2.8, but for Test 2.1 it was assumed that the rate of input of shale-coal mixture, which was fed intermittently during Test 2.1 was the total weight fed (weighed directly) divided by the duration of the test. The coal content of the mixture was deduced from the carbon content and from the analysis of the raw coal, and the coal ash, moisture, hydrogen and oxygen contents were also deduced from the analysis of the raw coal. The shale content of the mixture was assumed to be 100% ash, and the sulphate content of the total ash was assumed to be nil.

Until constant bed composition was achieved, it would be expected that the sulphur, calcium and magnesium contents of the bed would rise, and the ash, sodium and potassium contents would fall. Such behaviour was shown during Tests 2.1 and 2.2, although the sulphur emission had become stable during Test 2.1. In Tests 2.3 to 2.5, the variations in bed composition were small and random, probably reflecting to some extent analytical errors, e.g. the large loss of sodium from the bed in Test 2.5 resulting in a negative total sodium output.

3.2.2.6 Heat Balances

The heat balances are presented in Table 3.48. Good accountability of the heat input was obtained in Tests 2.2 to 2.5, but not in Test 2.1 during which a shale-coal mixture was fed intermittently to compensate for excessive loss of solids from the system via the primary cyclone. It is possible that this introduced errors in the measurements used in the calculations.

The main loss of potential heat (i.e. combustion efficiency) as in Test Series 1 was in the carbon carried over into the primary cyclone. The bulk of this loss ocurred in the finer fractions (less than 53 micron) as shown in Table 3.49.

3.2.2.7 Corrosion of metal specimens in the bed

The specimens were treated as for Test Series 1. The appearance of the tube assemblies after the test is described below:

Tubes 1 and 6 (1470°F metal temperature). There was a reddish film, matt on the PE16 and mottled on the SF316 and RF36. There was a black film on the Esshete.

Tube 2 (1290-1380°F) A brick red to cream film, flaking in places.

Tube 3 (1110-1170°F). Smooth, dark film on the high chrome alloys. The 1% and 2¼% Chrome alloys showed some blistering on the surface.

Tube 4 (840-1110°F) Similar to Tube 3. Smooth dull red/dark green film with slight blistering on the 1% and 2¼% Chrome alloys.

Tube 5 (630-930°F). Similar to Tubes 3 and 4.

The rates of weight loss measurements are given in Table 3.50 and the results are summarised in Table 3.51. The results of the metallographic examination of some of the specimens are given in Table 3.52. It is apparent from the results that corrosion was greater than in Test Series 1. The most likely explanation lies in the poor fluidisation experienced in Test Series 2, which could have caused high local bed temperatures.

It is also apparent that in this test, and in the other tests, the Tube 4 had consistently higher weight losses than would be expected from other tubes operating at similar temperatures. Tube 4 was not near a coal nozzle, but it must be concluded that it operated in a more corrosive environment than the other tubes.

3.2.2.8 Blade cascade and target rods

See Section 3.5.2.9 at end of Test Series 5.

3.3 Test Series 3

3.3.1 Objective of Test Series

To measure the emission of SO_2 and NO_X from the combustor when burning coal at 5 atm absolute pressure with dolomite 1337 addition at a nominal Ca/S ratio of 2. This was to be a completion of the Test Series 2 programme at a higher operating pressure.

3.3.2 General description of Test Series

3.3.2.1 Outline of Test Series

The test was carried out between 9th and 11th December 1970. The feed material was identical with that used in Test Series 2, but in order to obviate or delay the onset of the partial defluidisation which occurred in that test:- (a) the initial bed was a mixture of 60% shale and 40% of material from Test Series 1 with a median particle size of about 400 micron, and (b) the test was limited to a period of 45 hours.

Interruptions occurred after 7 and 23½ hours operation due to national power grid failures. After each interruption it required a progressively higher velocity to initiate fluidisation, signifying a gradual change in bed size. The test was completed satisfactorily with 91% of the operating time at 5 atm abs. pressure, but it is likely that defluidisation would have occurred eventually as in Test 2.

Two periods of steady operation were selected for computation of combustion efficiency, heat and mass balances. Samples of coal, primary and secondary cyclone fines, exhaust dust and bed extract were bulked before analysis to conform with these periods. Operating conditions are given in Table 3.53 and analyses of coal, dolomite, cyclone, exhaust dust and bed samples are given in Tables 3.54 to 3.59. Average gas composition measurements for each of the Test periods are given in Table 3.60.

3.3.2.2 Sulphur emission

Measurements of SO_2 and SO_3 were made at approximately hourly intervals using the "Shell" condensation and BCURA iodine absorption methods.

Results of measurements are tabulated in Table 3.61 and Fig. 3.6. Also shown in Fig. 3.6 are the variations in the approximate Ca/S stoichiometric ratio in the feed and the average operating conditions for each test period. The percentage of sulphur retained in each of the test periods is shown in Table 3.62.

3.3.2.3 NO_x emissions

Determinations of oxides of nitrogen in the exhaust gases were made in the early part of the test, using mainly the Saltzman method.[5] Results are tabulated in Table 3.63.

3.3.2.4 Retention of alkalis and chlorine

See Table 3.62 and 3.63A.

3.3.2.5 Mass Balances

The mass balances are shown in Tables 3.64 and 3.65, based on the assumptions already fully described in Section 2.8, unless otherwise stated in the footnotes to the tables. Constant bed composition was probably achieved early in Test period 3.1. Error in determining the sodium content of the bed at the end of Test 3.2 probably accounts for the large loss of sodium, resulting in negative output.

3.3.2.6 Heat Balances

The heat balances for Tests 3.1 and 3.2 are presented in Table 3.66.

3.3.2.7 Corrosion of metal specimens in the bed

The metal specimens were not examined after Test Series 3 and were left undisturbed until the end of Test Series 4.

3.4 Test Series 4

3.4.1 Objectives of Test Series

To measure the emission of SO_2 and NO_X from the combustor when burning Pittsburgh coal blended with finer dolomite 1337 than used hitherto.

3.4.2 General Description of Test Series

3.4.2.1 Outline of Test Series

The test was carried out between 11th and 15th January 1971 and lasted for 100 hours. The initial bed was a mixture of shale and bed material from earlier ("no dolomite") tests. For 96% of the time the operating pressure was 5 atm absolute, and the test was carried out at two levels of dolomite addition.

No difficulties were experienced in maintaining satisfactory fluidisation and there were no sintered agglomerations of any significant size in the bed at the end of the test. One interruption of 17 minutes occurred after 43 hours due to a failure in the air supply to the coal feeding plant, but no difficulties were experienced in restarting.

The rate of removal of bed material necessary to maintain a constant bed level was lower than in Test 3 (see Fig. 3.7).

Two periods of steady operation were selected for computation of combustion efficiency, heat and mass balances. Samples of coal, primary and secondary cyclone fines, exhaust dust and bed extract were bulked before analysis to conform with these selected periods. Operating conditions are given in Table 3.67 and analyses of coal, dolomite etc. samples are given in Tables 3.68 to 3.75. Average gas composition and measurements for each of the Test periods are given in Table 3.76 and the variations in bed temperature and gas composition in Tables 3.77 and 3.78.

3.4.2.2 Preparation of coal and dolomite

The raw dolomite was crushed, after drying and before screening, in a jaw crusher to produce a wider size distribution than was used in

Tests 2 and 3. This had the objective of achieving a lower mean bed particle size than in Test 2 when difficulties were experienced in maintaining fluidisation.

3.4.2.3 Sulphur emission

Measurements of SO_2 were made at approximately 90 minute intervals using the BCURA iodine absorption method[4]. No measurements of SO_3 were made.

Results are tabulated in Table 3.79 and Fig. 3.8. Also shown in Fig. 3.8. are the variations in the approximate Ca/S stoichiometric ratio in the feed and the average operating conditions for each test period The percentages of sulphur retained in both test periods are shown in Table 3.80.

During this test the Hartmann Braun SO_2 infra-red analyser was commissioned. The output was recorded continuously. Once certain commissioning problems had been overcome, excellent agreement was obtained between the infra-red analyser and the chemical method (Table 3.81). The recorded trace from the infra-red analyser showed that the SO_2 content of the gases was extremely sensitive to operating conditions. Fluctuations in coal feed rate which produced changes in O_2 concentration also produced immediate changes in SO_2 concentration (see Fig. 3.9). In fact, with the gas sampling systems being used, a change in coal feed rate was first apparent from the SO_2 analyser rather than the O_2 analyser.

3.4.2.4 NO_x emissions

Determinations of oxides of nitrogen were made throughout the test, using both the Saltzman[5] and Hersch[6] methods. Results are summarised in Table 3.82.

3.4.2.5 Retention of alkalis and chlorine

Determinations of sodium and potassium oxides and chlorine are summarised in Table 3.83, and the retention of alkalis and chlorine are shown in Table 3.80.

3.4.2.6 Mass Balances

The mass balances are shown in Tables 3.84 and 3.85, based on the assumptions already fully described in Section 2.2 unless otherwise stated in the footnotes to the tables. Constant bed composition was attained in Test 4.2.

3.4.2.7 Heat Balances

Heat balances for the test periods are presented in Table 3.86.

3.4.2.8 Corrosion of metal specimens in the bed

The specimens were treated as for the earlier tests. The appearance of the tube assemblies after the test was similar to that after Test Series 2.

The rates of weight loss measurements are given in Table 3.87 and the results are summarised in Table 3.88. Results of the metallographic examination of some of the specimens are given in Table 3.89.

3.4.2.9 Blade cascade and target rods

See Section 3.5.2.9 at end of Test Series 5.

3.5 Test Series 5

3.5.1 Objective of Test Series

To measure the emission of SO_2 and NO_X from the combustor when burning Pittsburgh coal blended with (a) limestone 18 at nominal Ca/S ratios of 2 and 3, and (b) fine dolomite 1337 at a nominal Ca/S ratio of 1.

3.5.2 General Description of Test Series

3.5.2.1 Outline of Test Series

The test was carried out between 22nd and 26th February 1971 and lasted for 100 hours. The initial bed was shale. For 98½ hours the operating pressure was 5 atm absolute. No difficulties were experienced in maintaining satisfactory fluidisation and there were no clinkered agglomerations in the bed at the end of the test. The first 40 hours of the test were with limestone 18 at a Ca/S mol ratio of about 2, the next 25 hours with limestone 18 at a Ca/S ratio of about 2.5; and the final 35 hours with dolomite 1337 at a Ca/S ratio of about 1.

The rate of removal of bed material necessary to maintain a constant bed level is shown in Fig. 3.7. Towards the end of the test the rate of accumulation of bed material was zero. This coincided with a gradual increase in the SO_2 concentration in the exhaust gases and a lower value of the Ca/S ratio in the feed. This lower ratio was probably due to segregation in the bunkers in the preparation plant since the Ca/S ratio was higher than intended in the first part of the period using dolomite.

Three periods of steady operation, corresponding to the three nominal operating conditions, were selected for computation of combustion efficiency, heat and mass balances. Samples of coal, primary and secondary cyclone fines, exhaust dust and bed extract were bulked before analysis to conform with these selected periods. Operating conditions are given in Table 3.90 and analyses of coal, dolomite, cyclone etc. samples are given in Tables 3.91 to 3.98.

Average gas composition measurements for each of the test periods are given in Table 3.99 and variations in bed temperature and gas composition are given in Tables 3.100 and 3.101.

3.5.2.2 Preparation of coal and limestone

The raw limestone was dried and crushed by an external supplier before screening on site.

3.5.2.3 Sulphur emission

The main measurements of the SO_2 concentration in the exhaust gases were made using the Hartmann-Braun infra-red analyser. The recorded trace from the ananlyser was averaged (by eye) every 30 minutes. Results are given in Table 3.102 and Fig. 3.10.

Measurements of SO_2 by the iodine absorption method were made every 2 to 3 hours. Comparison of these results with the infra-red values is shown in Table 3.103. Agreement was generally good.

Equilibrium SO_2 emissions were reached quickly when using limestone as the acceptor, but were as usual approached slowly (c. 15 to 20 hours) when dolomite was used.

The percentages of sulphur retained in the test periods are shown in Table 3.104.

3.5.2.4 NO_x emissions

A limited number of determinations of oxides of nitrogen were made throughout the test. Results are tabulated in Table 3.105.

3.5.2.5 Retentions of alkalis and chlorine

Determinations of sodium and potassium oxides and chlorine in the exhaust gases are summarised in Table 3.106 and the retention of alkalis and chlorine are shown in Table 3.104.

3.5.2.6 Mass Balances

The mass balances are shown in Tables 3.107 to 3.109, based on the assumptions already described in Section 2.8 unless otherwise stated in the footnotes to the tables. Changes in bed composition during Tests 5.1 and 5.2 would be expected to include gains in sulphur and calcium contents, and falls in ash and potassium contents;

these changes were observed, indicating that bed composition had not become constant although constant sulphur emission had been achieved. Similarly, in Test 5.3 following a change from limestone to dolomite changes in bed composition might be expected giving rises in sulphur, magnesium and potassium, and falls in ash and calcium. Since these changes were not observed it is concluded that constant bed composition had been achieved in Test 5.3.

3.5.2.7 Heat Balances

Heat balances for the test periods are summarised in Table 3.110.

3.5.2.8 Corrosion of metal specimens in the bed

The specimens were treated as for the earlier Test Series. The appearance of the tube assemblies after the test is described below:

Tube 1 and 6 (1450°F metal temperature). There was a reddish/brown film on the specimens, only lightly adhesive, having spalled on many specimens.

Tube 2 (1040-1200°F). A black polished film toward both ends with a red/brown coating on the middle sections which had spalled in places.

Tube 3 (750-840°F). A polished light-brown film overlaid with a rough black scale which had spalled.

Tube 4 (880-950°F). Similar to Tube 3.

Tube 5 (660-910°F). Similar to Tube 3.

The rates of weight loss measurement are given in Table 3.111 and the results are summarised in Table 3.112. Results of the metallographic examination are given in Table 3.113.

The operating temperatures of the different tubes were altered slightly for this test. More low-chrome ferritic specimens were used in this test, and Tube 3 was operated at a correspondingly lower temperature. It will be seen from Table 3.112 that weight losses on Tube 3 were lower than those on Tube 5, although the operating temperatures were similar. Prior to this Tube 3 had been operated at higher temperatures mainly with better quality materials. It will be seen from Fig. 2.3

that Tube 5 is in the vicinity of a coal nozzle and therefore might be expected to produce higher corrosion rates. This would appear to be confined to the low chrome metals, however, since in earlier tests there was no evidence that losses for better materials were higher on Tube 5 than would be expected.

3.5.2.9 Blade cascade and target rods

At the beginning of the programme the Proteus nozzle segment had been used for 400 hours. The blades were examined after each Test Series. Mechanical cleaning (by brushing) was carried out on one blade after Test Series 1, the other blade was not cleaned, except by "soft-blasting" as described below, and at the end of the programme had remained uncleaned for 740 hours.

The appearance of the blades did not vary greatly from test to test and typical appearances after Tests Series 1, 2 and 3 are shown in Fig.3.11. Usually there was a light accumulation of dust on the leading edge with flecks of dust adhering to the concave faces and negligible deposition on the convex faces. There were no signs of sintered deposits or of erosion. There was not sufficient material adhering to the blades for analysis, but there was sufficient dust on the side walls of the cascade holder after Test Series 2 to show that it had a similar composition to the exhaust dust passing over the cascade (see Table 3.114).

Slightly heavier accumulations of dust on the blades occurred after Test Series 1. Between Test Series 1 and 2 a short (10 hour duation) test was carried out, outside the APCO remit. Towards the end of this test, 2 lb of crushed fruit stone was injected upstream of the cascade over a period of 1 minute. This successfully removed the accumulations of dust.

At the beginning of the programme the target rods had been in use for 300 hours. They were inspected after each Test Series, but were not cleaned except by "softblasting" as described in the previous paragraph. The rods usually had a small knife-edge of deposit on their leading face and had developed a considerable "tail". Weighing, sectioning and examination under a microscope of one of the rods revealed no signs of erosion or corrosion.

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The programme was supervised by A.G. Roberts and was carried out in the Process Development Group (Director - H.R. Hoy) of BCURA Industrial Laboratories Ltd.

Members of staff of BCURA who took part in the experimental work included:

S. Badzioch
C. Chanter
E.S. Dingoor
M. Fisher
W.A. Gearing
F.W. Hood
J. Kobak
A.W. Lindsay
R.S.E. Leslie
A.G. Roberts
J.A.C. Samms
J.E. Stantan
D.G. Warrilow
D.M. Wilkins
M.A. Wright
J.M. Wyrill

Design work was carried out by R.L. Johnson.

Table A.2.2.1 Details of cyclones

Duty	Recirculation	Primary cyclone (1st stage gas cleaning)	Secondary cyclone (2nd stage gas cleaning)
Material: body	A.I.S.I.321	Incoloy DS	Incoloy DS
flanges	A.I.S.I.321	En 58 b	En 58 b
dimensions (inches)*			
Gas inlet: height, h	$7\frac{3}{8}$	$6\frac{1}{4}$	$6\frac{1}{4}$
: width, w	$4\frac{1}{2}$	$3\frac{1}{8}$	$2\frac{3}{8}$
Gas outlet: diameter, De	$7\frac{1}{2}$	5	5
: length, Le	$8\frac{3}{4}$	8	8
Barrel: dimeter, D	10	10	10
: length, L	$12\frac{1}{4}$	$13\frac{3}{4}$	$13\frac{3}{4}$
Cone: length, L_2	$20\frac{1}{8}$	20	20
Dust exit: diameter, D_d	4	3	3
Performance characteristics**			
Normal gas flow, ft^3/s	15.5	15.5	15.5
Inlet velocity, ft^3/s	65	115	140
Outlet velocity, ft^3/s	50	115	115
Typical pressure drop, lb/in^2 ***	0.6	1.3	3.8

* See Fig. A.2.2.4.

** based on cross section area of combustor of 7.75 ft^2, a fluidising velocity of 2 ft/s and operation at circa 5 atm pressure and 1470°F.

*** the pressure drops also include ducting losses and pressure changes due to acceleration of gases.

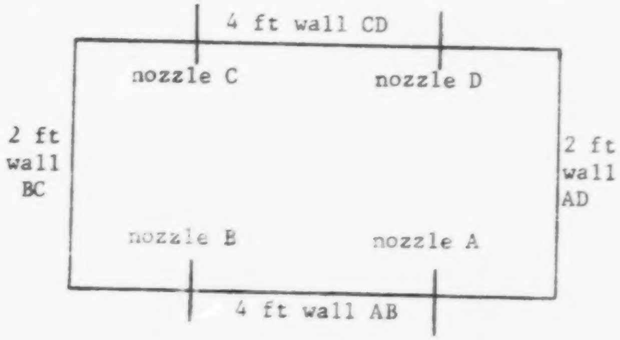
Table A.2.2.2 Location of thermocouples within the pressure shell

Location and duty	Number of thermocouples
Plenum chamber	2
Air preheat tubes: outlets	6
Corrosion tubes: metal temperatures,	
a. top upstream	6
b. bottom upstream	6
c. top downstream	6
d. bottom downstream	6
Corrosion tubes: air outlets	4
Bed	16
Bed cooling circuits: inlet	1
: outlets	13
Freeboard	9
Freeboard cooling circuits: outlets	3
Coal nozzle cooling shrouds: outlets	4
Heat transfer loops	3
Bed ash blowdown leg	1
Dipleg and recirculation cyclone	2
Dust cleaning cyclones and blowdowns	5
Cascade inlet	2
Cascade outlet	2
Quench section bellows	2
Combustor surface	1
Space beneath combustor	2
Space above combustor	1
Suspension beam	1
Radio-active source	4
	1
Total	107

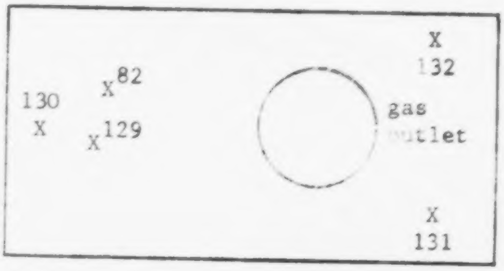
Table A.2.2.3 Details of location of thermocouples in the bed and freeboard

Thermocouple reference (Data logger channel)	Height above distributor plate in	Insertion in	From*	Location*
In bed				
101	1¼	1¼	dist.plate	Below nozzle D
102	2⅛	3	wall AB	adjacent nozzle A
106	2⅛	3	wall BC	centre
107	2⅛	3	wall AD	centre
108	3¼	2	wall CD	2½ in. from wall AD
109	3¼	2	wall CD	3¼ in. from wall BC
110	3⅜	2	wall AB	centre
112	4¾	2	wall AB	4 in. from wall BC
117	12¾	1	wall CD	centre nozzle C
113	12⅞	1	wall CD	adjacent nozzle C
115	12⅞	1	wall AB	centre
118	15⅞	1	wall CD	adjacent nozzle D
119	35¾	3	wall AB	above nozzle B
120	35¾	3	wall AB	above nozzle A
121	35¾	3	wall CD	above nozzle D
122	35¾	3	wall CD	above nozzle C
In freeboard				
125	77	3	wall AB	above nozzle A, 11 in. from wall AD
126	77	3	wall AB	above nozzle B, 11 in. from wall BC
127	77	3	wall CD	above nozzle C, 11 in. from wall BC
128	77	3	wall CD	above nozzle D, 11 in. from wall AD
129	106¾	13¼	cover plate	see right hand diagram below
130	106¾	13¼	" "	" "
131	106¾	13¼	" "	" "
132	106¾	13¼	" "	" "
82	106¾	13¼	" "	" "

* see left hand diagram below. nozzle denotes coal nozzle.



Plan view of combustor, looking downwards



Plan view looking down on cover plate

Table A.2.3.1 Operating conditions during Test Series 1

Coal	Welbeck	
Coal size (upper limit)	1587	µm
Acceptor size (upper limit)	1587	µm
Coal rate	370-390	lb/h
Fluidising velocity	1.95	ft/s
Bed temperature	1455	°F
Combustor pressure	3.5	atm abs
Bed height	3.75	ft

Test No.		1.1	1.2	1.3	1.4	1.5
Elapsed time from start of test series	start, h	4.45	10.95	23.12	58.62	73.62
	end, h	8.95	22.62	50.62	73.28	99.95
Acceptor		None	U.K. Dolomite	U.K. Dolomite	U.K. Dolomite	U.K. Dolomite
Stoichiometric ratio		0	0.77	0.73	0.91	0.92

Table A.2.3.2 Analysis of spot (coal + dolomite) samples

Test Series 1

Sample Ref	Sample time min	Moisture %	"Ash" %	CO_2 %	Size grading: % within stated size grade						Median diameter μm
					-1588 + 794 μm	-794 +500 μm	-500 +211 μm	-211 +152 μm	-152 + 75 μm	- 75μm	
1	82	5.6	21.1	0.5	9.8	22.4	42.7	7.7	7.7	9.7	400
2	267	5.7	13.6	0.3	9.2	20.2	39.1	8.1	8.9	14.5	400
3	447	5.7	13.8	0.2	8.3	18.8	43.3	6.9	8.3	14.4	400
4	607	5.6	17.1	1.9	9.9	23.5	40.7	6.9	7.5	11.5	400
5	777	4.9	21.7	2.6	8.4	18.7	47.4	5.9	6.6	13.0	400
6	952	5.2	20.1	2.0	8.8	21.4	42.5	7.4	5.6	14.3	370
7	1147	4.6	26.6	3.7	9.4	21.2	50.4	5.6	5.5	7.8	400
8	1317	4.4	23.2	2.9	12.1	24.7	42.7	6.3	5.9	8.3	430
9	1507	5.1	20.2	2.8	15.1	31.2	39.9	5.8	5.5	7.5	450
10	1682	5.2	19.3	2.5	13.1	22.6	42.2	5.4	6.3	10.4	400
11	1867	5.0	20.8	2.7	14.6	24.5	40.0	5.3	5.4	10.2	440
12	2007	4.8	20.0	2.8	15.0	26.4	41.5	4.5	4.7	7.9	460
13	2187	4.8	19.5	2.8	14.8	29.1	39.6	5.2	4.4	6.9	470
14	2397	4.6	22.0	3.3	16.8	27.6	41.4	3.9	3.9	6.4	470
15	2575	5.0	18.6	2.1	13.5	25.1	41.5	5.9	5.3	8.7	450
16	2624	4.8	21.8	2.6	12.2	23.7	46.1	4.5	4.5	9.0	420
17	2758	4.6	20.2	2.2	16.8	25.6	38.3	5.4	5.0	8.9	460
18	2952	4.9	17.5	2.2	20.0	40.1	33.4	3.9	4.3	8.3	500
19	3127	4.9	16.2	1.8	18.9	27.1	32.3	4.5	4.9	12.3	470
20	3292	5.3	16.2	1.7	17.4	27.2	35.5	4.9	5.0	10.0	470
21	3352	5.0	18.8	3.3	18.8	26.0	38.9	3.5	4.1	8.9	460
22	3437	5.0	19.2	3.4	12.7	23.2	37.5	6.3	6.7	13.6	400
23	3663	5.0	19.4	3.1	11.4	21.4	44.9	5.2	5.9	11.2	410
24	3842	4.9	19.4	4.1	14.5	24.4	38.4	5.9	6.2	10.7	430
25	4012	4.9	17.7	3.3	11.6	22.8	43.4	5.0	5.8	12.4	400
26	4199	4.7	18.7	3.6	11.4	22.8	39.6	6.6	7.2	12.4	380
27	4387	4.6	17.9	2.1	10.3	21.9	41.0	7.4	7.9	11.5	380
28	4567	4.3	17.8	3.9	13.7	22.6	38.7	6.3	9.0	11.7	400
29	4747	4.5	18.9	4.2	14.4	21.7	41.7	4.8	5.9	11.5	410
30	4967	4.9	17.0	2.9	13.1	25.1	38.2	5.8	6.2	11.6	400
31	5102	4.7	16.8	2.9	14.9	23.0	42.6	4.9	5.6	12.0	410
32	5285	5.1	15.7	2.6	14.3	24.2	37.2	5.7	6.3	12.3	390
33	5463	4.6	15.5	3.6	13.0	21.9	41.1	5.3	5.8	12.9	390
34	5641	4.8	17.6	3.7	12.9	21.7	44.7	6.6	7.4	14.7	320
35	5822	4.7	15.9	3.1	13.1	22.2	35.7	6.4	7.1	15.5	390
36	5989	5.1	3.3	12.7	21.8	36.5	36.5	6.4	7.6	15.0	370

Analyses are given as weight % on an "as fired" basis.

Table A.2.3.3 Analysis of bulked samples of (coal plus dolomite)

Test Series 1

Test	1.1	1.2	1.3			1.4	1.5	
Sample Ref	36609	36627	36628	36629	36630	36631	36632	36633
Sample period min	267 to 447	777 to 1317	1507 to 1867	2007 to 2397	2575 to 2952	3663 to 4387	4567 to 5285	5463 to 5988
Moisture	5.9	4.8	5.1	4.7	4.8	4.8	4.6	4.8
"Ash"	13.9	22.9	20.1	20.5	18.6	18.6	17.6	16.0
Sulphur	1.2	1.3	1.3	1.2	1.2	1.2	1.2	1.1
Carbon dioxide	0.2	2.8	2.7	3.0	2.2	3.2	3.5	3.3
CaO	2.3	9.1	9.4	10.0	8.4	12.0	12.8	14.2
MgO	1.6	5.6	6.0	6.4	5.3	7.6	8.2	9.2
Na_2O	-	1.6	1.2	1.4	1.5	1.4	1.7	1.9
K_2O	-	2.8	2.5	2.7	2.5	2.4	2.4	2.4

Moisture, "Ash", S and CO_2 are given as weight percent on an "as fired basis" and refer to (coal + dolomite) mixture fed to the combustor.

CaO, MgO, Na_2O and K_2O are given as weight percent of the "Ash".

Table A.2.3.4 Analysis of bulked samples of (coal plus dolomite)

Test Series 1

Test		1.1	1.2 & 1.3	1.4 & 1.5
Sample Ref		36609	36634	36635
Proximate analysis				
Moisture	%	5.9	5.1	5.1
Volatile Matter	%	36.9	39.3	39.3
Fixed Carbon	%	50.6	45.4	47.4
Ash	%	13.9	20.1	16.8
Carbon dioxide	%	0.2	2.4	3.3
Ultimate Analysis				
Ash	%	14.8	21.2	17.7
Carbon	%	70.3	63.2	66.1
Hydrogen	%	4.5	4.1	4.2
Nitrogen	%	1.5	1.5	1.4
Sulphur	%	1.3	1.4	1.3
Oxygen + errors	%	7.0	7.7	8.8
Chlorine	%	0.61	0.55	0.56
Forms of Sulphur				
Pyritic	%	0.32	0.40	0.30
Sulphatic	%	0.02	0.02	0.02
Organic	%	0.86	0.88	0.88
Total	%	1.2	1.3	1.2
Calorific Value	Btu/lb	14813	n.d.	n.d.
Swelling Number		1	1	1

The ultimate analysis is stated on a dry basis, volatile matter content and calorific value are stated on a d.a.f. basis. The remaining analyses are given on an 'as fired' basis.

For ash analyses, see Table 3.5.

n.d. = not determined.

Table A.2.3.5 Ash analysis of bulked samples of (coal plus dolomite)

Test Series 1

Test	1.1	1.2 & 1.3	1.4 & 1.5
Sample Ref.	36609	36634	36635
Ash Analysis			
SiO_2	57.8	47.8	41.0
Al_2O_3	23.2	19.1	17.3
Fe_2O_3	6.8	5.9	5.2
CaO	2.3	8.4	12.2
MgO	1.6	6.1	8.6
Na_2O	2.2	1.6	1.8
K_2O	3.0	2.6	2.4
TiO_2	1.0	0.8	0.8
Mn_3O_4	<0.1	0.1	0.1
P_2O_5	0.2	0.2	0.2
SO_3	1.8	6.2	9.5
Total	99.9	98.8	99.2
Ash Fusion			
Initial deformation °F	2120	2170	2160
Hemisphere °F	2440	2210	2190
Flow °F	2730	2550	2320

Ash analyses given on a weight percent basis, and refer to the (coal + dolomite) analyses given in Table A.2.3.4.

Ash fusion determined in H_2/CO_2.

Table A.2.3.6 Analysis of raw dolomite

Test Series 1

Test		1.2 & 1.3	1.4 & 1.5
Sample Ref		36602	36603
Analysis			
CaO	%	29.2	29.4
MgO	%	21.5	21.4
Na_2O	%	1.3	0.5
K_2O	%	0.6	0.1
SO_3	%	0.1	0.1
CO_2	%	46.7	45.8

Analysis given on weight percent basis
20 incremental samples were taken from the dolomite
added to the coal stream during Tests 1.2 & 1.3 to make up Sample 36602
37 incremental samples were taken from the dolomite
added to the coal stream during Tests 1.4 & 1.5, to make up Sample 36603

Table A.2.3.7 Analysis of primary cyclone fines collected by dry sampling system

Test Series 1

Test		1.1	1.2		1.3			1.4			1.5	
Sample Ref		1520	1521	1522	1523	1524	1525	1526	1527	1528	1529	1530
Sample period min		273 to 493	604 to 970	1037 to 1326	1387 to 1868	1926 to 2405	2523 to 2951	3009 to 3311	3543 to 4209	4270 to 4391	4446 to 5407	5464 5o 5997
Carbon	%	13.4	11.5	8.4	7.6	6.0	6.2	8.5	5.8	6.7	5.5	5.3
Hydrogen	%	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Sulphur	%	0.7	1.5	2.2	2.6	2.9	2.8	2.7	3.4	3.6	3.7	4.2
Carbon dioxide	%	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.6	0.4	0.4	0.7
Chlorine	%	0.05	-	-	-	-	-	0.17	-	-	-	0.46
CaO	%	2.0	3.5	4.9	6.0	7.0	6.7	6.5	10.0	9.7	10.2	12.6
MgO	%	1.4	2.5	3.4	4.3	4.9	4.7	4.8	6.6	6.5	7.2	8.6
Na_2O	%	1.4	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.4	1.7
K_2O	%	2.6	2.6	2.6	2.6	2.6	2.6	2.5	2.4	2.3	2.3	2.2
Size Grading	Wt. % within stated size grade											
-1588 + 794	μm	1	1	1	1	2	2	2	2	3	2	1
- 794 + 500	μm	7	6	7	7	8	8	8	8	9	7	6
- 500 + 251	μm	19	18	18	19	18	20	17	18	19	16	14
- 251 + 152	μm	9	10	11	12	15	15	12	12	14	12	12
- 152 + 75	μm	13	14	17	16	18	15	16	16	18	16	17
- 75 + 53	μm	6	8	7	8	7	8	6	8	6	8	6
- 53 + 0	μm	45	44	37	36	33	32	40	36	31	39	43
Median dia.	μm	70	70	90	90	115	120	90	100	120	85	75

Analyses are given as weight percent on an "as received" basis.
% Carbon does not include carbon present as carbon dioxide.
Samples were taken approximately hourly and, except for chlorine, were bulked over the periods indicated. % chlorine determined on a single sample taken within the period indicated.

Table A.2.3.8 Analysis of Secondary Cyclone fines

Test Series 1

Test		1.1	1.2		1.3			1.4			1.5	
Sample Ref		1534	1535	1536	1537	1538	1539	1540	1541	1542	1543	1544
Sample period min		259 to 559	679 to 1042	1047 to 1369	1369 to 1818	1955 to 2375	2554 to 2974	2974 to 3283	3517 to 4245	4245 to 4422	4422 to 5443	5443 to 5997
Carbon	%	9.2	6.4	8.1	6.4	5.0	5.7	5.0	5.9	6.8	3.9	2.3
Sulphur	%	1.2	2.2	2.8	3.2	3.8	3.2	3.2	3.9	3.6	3.9	4.2
Carbon dioxide	%	-	-	0.2	-	-	0.2	0.1	-	0.7	-	0.5
Chlorine	%	0.37	-	-	-	-	-	0.65	-	-	-	0.92
CaO	%	3.5	5.5	7.0	7.8	9.5	8.1	7.7	14.6	11.5	11.7	15.2
MgO	%	1.5	3.0	4.6	6.1	7.3	7.0	6.9	8.9	4.0	10.4	12.2
Na_2O	%	2.3	1.9	1.6	1.8	1.9	1.8	2.1	2.8	1.7	2.5	2.9
K_2O	%	2.5	2.0	1.8	2.0	2.0	2.1	2.3	1.6	1.9	2.4	2.4
Size Grading	Wt. % within stated size grade											
- 75 + 60	μm	0	2	0	0	1	1	0	0	0	1	0
- 60 + 50	μm	0	4	0	0	1	1	0	0	0	2	2
- 50 + 40	μm	0	1	2	1	1	1	1	4	1	5	0
- 40 + 30	μm	0	3	2	2	2	1	6	2	2	5	7
- 30 + 20	μm	2	8	3	6	2	2	5	5	7	4	5
- 20 + 15	μm	7	9	11	8	5	6	6	7	9	14	5
- 15 + 10	μm	19	14	20	16	14	20	15	14	18	14	11
- 10 + 5	μm	56	47	42	49	47	45	19	49	47	34	49
- 5 + 0	μm	16	12	21	17	27	21	20	17	16	23	22
Median dia.	μm	8	9	7	8	7	7.4	7	8	8	8	7
Mean dia. D_p	μm	6	7	6	6	6	6.4	6	6	7	7	6

Analyses are given as weight percent, on an "as received" basis.
Carbon does not include carbon present as CO_2.
Samples were taken approximately hourly and, except for chlorine, were bulked over the periods indicated. % Chlorine determined on a single sample taken within the period indicated.
Size gradings were obtained by a Coulter Count on the material passing through a 75 micron sieve. Except for Sample 1536, the +75 micron content was less than 2%. For Sample 1536, 4.8% was +75 micron.

D_p is given by $\frac{1}{D_p} = \sum \frac{X_{ij}}{(d_i d_j)^{0.5}}$ where X_{ij} is the weight fraction between particle size limits d_i and d_j.

[illegible] Test Series 1 Analysis of Exhaust Dust

Test		1.1	1.2	1.3	1.4	1.5
Sample Ref		1548	1549	1550	1551	1552
Carbon	%	9.0	7.5	6.7	11.7	5.5
Sulphur	%	2.1	2.9	3.6	3.1	3.0
Chlorine	%	1.1	-	1.2	-	1.1
CaO	%	4.1	4.8	6.4	7.6	9.4
MgO	%	1.9	5.1	9.1	15.2	17.1
Na_2O	%	2.4	1.7	2.3	1.3	2.8
K_2O	%	2.3	1.8	2.2	1.6	2.4
Size Grading		% within stated size grade				
-75 +60 µm		5	3	4	6	12
-60 +50 µm		3	9	1	2	1
-50 +40 µm		2	5	9	3	3
-40 +30 µm		7	3	6	3	6
-30 +20 µm		7	3	0	2	4
-20 +15 µm		7	11	6	6	3
-15 +10 µm		12	8	13	10	13
-10 + 5 µm		42	38	39	42	34
- 5 + 0 µm		15	20	22	26	24
Median diameter µm		9	9	8	7	8
Mean diameter, D_p µm		8	7	7	6	7

Analyses are given as weight per cent on an 'as received' basis.

% carbon does not include carbon present as carbon dioxide.

Size gradings were obtained by a Coulter Count on material passing a 75µm sieve. Sample 1548 contained 4.3% by weight of +75 µm particles; the remaining samples had zero +75 µm content.

D_p as defined in Table A.2.3.8.

Table A.2.3.10 Analysis of Bed Material

Test Series 1

Test	1.1	1.2	1.3				1.4		1.5				
Sample time min	715 to 865	1225	1860	2260	2865	3175	3825	4370	4890	5475	5790	5915	
Sample Ref	1556	1557	1558	1559	1560	1561	1562	1563	1564	1565	1566	1567	1568
Carbon %	0.1	<0.1	0.3	0.2	0.3	0.2	0.2	0.1	0.2	0.2	<0.1	0.3	<0.1
Sulphur %	1.1	2.3	2.5	1.4	2.8	2.7	2.5	3.6	3.6	4.0	4.4	4.7	4.3
Carbon dioxide %	-	-	-	-	-	-	-	0.7	-	-	0.8	-	0.6
Chlorine %	-	-	-	-	-	0.10	-	-	-	-	0.24	-	0.28
CaO %	3.0	6.3	6.5	3.7	7.2	6.9	7.5	10.6	10.7	10.2	11.5	13.1	11.7
MgO %	2.3	8.1	4.3	2.8	4.8	4.4	4.8	6.8	7.3	5.3	7.7	8.2	8.6
Na_2O %	1.6	1.6	2.0	1.8	1.6	2.0	1.6	2.4	2.2	1.3	2.4	3.0	1.6
K_2O %	3.3	3.0	2.9	3.3	2.9	3.2	2.9	3.1	3.0	2.6	2.9	3.1	2.5
Size Grading	% within stated size range												
-1588+794μm	10	3	5	14	6	13	10	8	6	10	9	8	15
- 794+500μm	34	11	20	32	20	30	27	21	19	24	22	20	29
- 500+251μm	45	27	43	35	39	35	37	31	34	32	35	31	44
- 251+152μm	7	18	16	10	15	11	13	16	17	16	16	18	11
- 152+ 75μm	1	20	7	6	6	7	8	14	10	12	8	14	1
- 75+ 53μm	2	8	5	1	9	2	3	4	8	3	6	3	-
- 53+ 0μm	1	13	4	2	5	2	2	6	6	3	4	6	-
Median dia. μm	470	190	340	460	350	450	400	310	310	370	360	300	450

Analyses are given as weight percent on an 'as received' basis. % Carbon does not include carbon present as carbon dioxide.
1568 sample refers to material remaining in bed after the test series.
Sample 1556 to 1567 refer to material removed via the weir during the test series.

Table A.2.3.11 Gas composition measurements

Test Series 1

Test		1.1	1.2	1.3	1.4	1.5
Elapsed time from start of test series	Start, h	4.45	10.95	23.12	58.62	73.62
	End, h	8.95	22.62	50.62	73.28	99.95
Operating Conditions	Ca/S mol ratio	0	0.77	0.73	0.91	0.92
	Variable parameters	No Acceptor	Acceptor U.K. Dolomite	Acceptor U.K. Dolomite	Acceptor U.K. Dolomite	Acceptor U.K. Dolomite
Gas composition % by volume (dry gas)	CO_2	15.1	14.9	15.1	15.1	15.2
	CO	0.10	.05	.03	.03	.02
	O_2	3.8	4.2	4.6	5.1	4.8
Gas composition p.p.m. by volume (dry gas)	SO_2	1020	620	430	100	150
	SO_3	9	14	14	8	5
	NO_x	40	-	80	120	130
	Cl	490	590	640	460	330
	Na_2O	1.5	1.2	0.9	0.5	0.5
	K_2O	0.4	0.3	0.2	0.2	0.2

Table A.2.3.12 Variation of gas composition and bed temperature during test

Test Series 1

Numbers in columns are % of time in stated range

Gas Analysis

	<2% O_2	2 to 4% O_2	4 to 6% O_2	>6% O_2
Test 1.2 & 1.3	4	37	44	15
Test 1.4 & 1.5	2	23	68	8

Gas Analysis

	0 to 0.025% CO	0.025 to 0.05% CO	> 0.05% CO
Test 1.2 & 1.3	33	51	16
Test 1.4 & 1.5	75	24	1

Bed Temperature

		<1400°F	1400 to 1436°F	1436 to 1472°F	1472 to 1508°F	> 1508°F
1¼" to 5" above distributor	Test 1.2 & 1.3	4	34	48	13	1
	Test 1.4 & 1.5	3	38	53	6	0
13" to 16" above distributor	Test 1.2 & 1.3	1	25	57	17	0
	Test 1.4 & 1.5	2	30	58	10	0
36" above distributor	Test 1.2 & 1.3	0	13	60	27	0
	Test 1.4 & 1.5	0	8	66	26	0

Table A.2.3.13 Test Series 1 Measurements of SO_2 and SO_3 in exhaust gases

Time from start mins	SO_2 p.p.m. (v/v)	SO_3 p.p.m. (v/v)	Time from start mins	SO_2 p.p.m. (v/v)	SO_3 p.p.m. (v/v)
65	772	15.3	2857	434	22.5
85	1682	30	2919	412	9.9
105	930	21.6	2974	510	5.4
124	1176	12.4	3026	634	7.5
142	909	9.9	3111	447	"
161	738	4.8	3162	477	-
260	854	10.8	3223	537	17
300	1008	9.6	3282	491	20
328	941	1.9	3332	514	16
349	-	12.5	3378	255	4
382	1067	1.5	3402	207	2.3
402	1026	12.3	3421	191	"
434	1101	5.4	3443	133	5
454	1037	26.7	3467	186	6
493	1035	6.1	3543	117	4.8
507	993	13.0	3602	113	0
530	989	37	3665	115	0
548	918	14.6	3721	79	0
575	732	3.9	3784	93	9.5
604	729	9.2	3840	97	28.7
622	780	2.4	3911	95	8.6
647	669	16.4	3968	123	23
674	599	4.9	4100	120	5.1
752	810	6.6	4155	123	1.6
826	596	3.9	4244	112	14
885	677	-	4300	166	4.6
948	657	2.2	4357	210	1.0
1015	476	32.7	4412	293	4.4
1068	554	-	4461	277	6.2
1087	516	20.7	4544	212	3.5
1205	626	14.2	4592	200	4.0
1248	755	24.6	4658	138	9
1336	522	19.1	4708	88	2.5
1397	598	-	4764	86	4
1488	542	-	4825	98	7.4
1589	451	10.6	4887	195	3.9
1667	527	9.0	4955	156	12
1722	466	9.8	5016	234	9.1
1866	582	17.5	5089	181	4
1922	386	13.4	5159	143	3.3
1972	362	21.7	5222	201	9.5
2039	288	16.5	5279	178	6.8
2109	315	5.2	5339	233	3.8
2162	279	16.4	5395	205	2.9
2236	340	4.1	5452	132	5.5
2285	262	19.7	5533	99	2.7
2349	268	5.5	5582	81	3.6
2404	270	10.4	5670	105	4
2522	504	9.8	5733	105	3
2577	524	16.6	5789	92	3.6
2639	568	17.5	5845	92	2.6
2712	587	15.4	5904	108	10.8
2801	522	29.3	5972	89	2

Table A.2.3.14 Percentage Retention of Sulphur, Alkalis and Chlorine

Test Series 1

Test No.	1.1	1.2	1.3	1.4	1.5
Stoichiometric Ratio	0.00	0.77	0.73	0.91	0.92
Total Ca/S Mol Ratio	0.15	0.92	0.88	1.06	1.07
Retention %					
Sulphur	8.9	51.8	62.3	90.4	85.5
Sodium	99.0	99.3	99.4	99.6	99.6
Potassium	99.8	99.9	99.9	99.9	99.8
Chlorine	1.7	3.5	4.1	12.9	20.6
Reduction %					
Sulphur Emission	Nil	38.8	56.7	89.2	85.1

% Retention of sulphur, sodium and potassium
= 100 (Total Input-Output in Gas)/Total Input

% Retention of chlorine
= 100 (Total Output-Output in Gas)/Total Output

% Reduction of sulphur emission
= 100 (Emission without acceptor-Emission observed)/(Emission without acceptor)

Emission without acceptor (Test 1.1) assumed to be 1031 p.p.m. v/v in dry gas

Stoichiometric Ratio assumed = (Total Ca/S Mol Ratio - 0.15)

Table A.2.3.15 Concentration of NO_x in combustion gases
Test Series 1

Time from Start min.	NO_x concentration p.p.m. (v/v) Av.	Range	No. of determinations	Method
117 - 247	37	18- 62	4	Saltzman
1497 - 1527	66	48- 82	4	"
2937 - 2997	93	66-125	3	"
4267 - 4392	120	115-125	Continuous	Hersch
4392 - 4437	98	85-112	4	Saltzman
4425 - 4437	95	80-110	Continuous	Hersch
4452 - 4722	115	85-150	"	"
5817 - 5847	209	165-241	3	Saltzman

Table A.2.3.15A Determinations of Alkalis and Chlorine in Flue Gas
Test Series 1

Time, hours from Start	Concentration, μg/l dry gas			Concentration, p.p.m. by volume, dry gas		
	Cl	Na_2O	K_2O	Cl	Na_2O	K_2O
4.42	782	4.1	1.5	494	1.5	0.4
12.57	926	3.4	1.3	585	1.2	0.3
25.75	1259	3.2	1.0	796	1.2	0.2
41.55	779	1.6	0.6	492	0.6	0.1
53.97	588	1.8	1.2	372	0.7	0.3
63.80	586	1.0	0.7	370	0.4	0.2
73.70	867	1.5	0.9	548	0.5	0.2
88.72	594	1.2	0.4	375	0.4	0.1
97.93	441	1.8	1.1	279	0.7	0.3

Note: The quantities of Cl, Na and K measured are assumed to exist in vapour form.

Table A.2.3.10 Mass Balances for Test 1.1

Test Series 1

Flow Rates in lb /h

	Total	Ash	Carbon	Hydrogen	Nitrogen	Oxygen
Inputs						
Coal	369	50.37	244.3	17.93	5	44.8
No Acceptor	-	-	-	-	-	-
Main Air	3275	-	0.4	0.87	2508	765.6
Conveying Air	315	-	0.0	-	242	73.2
Dipleg Nitrogen	17	-	-	-	17	-
Total Input	3976	50.37	244.7	18.80	2772	883.6
Outputs						
Gained by Bed	-	-	-	-	-	-
Primary Cyclone	55	47.02	7.4	-	-	0.6
Secondary Cyclone	2	1.32	0.1	-	-	0.0
Exhaust Dust	0	0.37	0.0	-	-	0.0
Flue Gas	3918	-	222.6	18.80	2780	890.9
Total Output	3976	48.71	230.2	18.80	2780	891.6

	Sulphur	Calcium	Magnesium	Sodium	Potassium	Chlorine
Inputs						
Coal	4.428	0.8431	0.4950	0.837	1.28	1.99
No Acceptor	-	-	-	-	-	-
Main Air	-	-	-	-	-	-
Conveying Air	-	-	-	-	-	-
Dipleg Nitrogen	-	-	-	-	-	-
Total Input	4.428	0.8431	0.4950	0.837	1.28	1.99
Outputs						
Gained by Bed	-	-	-	-	-	-
Primary Cyclone	0.388	0.7933	0.4687	0.576	1.20	0.03
Secondary Cyclone	0.018	0.0378	0.0137	0.026	0.03	0.01
Exhaust Dust	0.009	0.0127	0.0050	0.008	0.01	0.00
Flue Gas	4.034	-	-	0.008	0.00	2.14
Total Output	4.450	0.8438	0.4873	0.618	1.24	2.18

Bed Composition assumed not to have changed during the test.
Chlorine content of Bed assumed.

Table A.2.3.17 Mass Balances for Test 1.2

Test Series 1

Flow Rates in lb/h

	Total	Ash	Carbon	Hydrogen	Nitrogen	Oxygen
Inputs						
Coal	365	71.78	220.4	16.36	5	44.6
Dolomite	21	11.14	2.7	-	-	7.1
Main Air	3238	-	0.4	0.68	2481	756.0
Conveying Air	274	-	0.0	-	210	63.6
Dipleg Nitrogen	15	-	-	-	16	-
Total Input	3913	82.91	223.5	17.03	2712	871.3
Outputs						
Gained by Bed	-5	-9.33	-0.2	-	-	2.9
Weir Solids	28	26.43	0.0	-	-	0.8
Primary Cyclone	64	54.24	6.4	-	-	1.9
Secondary Cyclone	1	0.95	0.1	-	-	0.0
Exhaust Dust	0	0.36	0.0	-	-	0.0
Flue Gas	3825	-	215.2	17.03	2715	872.7
Total Output	3913	72.65	221.6	17.03	2715	878.3
	Sulphur	Calcium	Magnesium	Sodium	Potassium	Chlorine
Inputs						
Coal	5.010	1.381	0.271	0.85	1.95	1.89
Dolomite	0.008	4.368	2.714	0.20	0.10	-
Main Air	-	-	-	-	-	-
Conveying Air	-	-	-	-	-	-
Dipleg Nitrogen	-	-	-	-	-	-
Total Input	5.018	5.749	2.986	1.05	2.05	1.89
Outputs						
Gained by Bed	1.913	3.463	1.484	0.06	-0.63	-0.00
Weir Solids	0.557	1.105	0.487	0.33	0.69	0.03
Primary Cyclone	1.191	1.932	1.145	0.62	1.39	0.06
Secondary Cyclone	0.028	0.050	0.025	0.01	0.02	0.00
Exhaust Dust	0.013	0.015	0.013	0.01	0.01	0.00
Flue Gas	2.419	-	-	0.01	0.00	2.48
Total Output	6.120	6.565	3.156	1.03	1.48	2.57

Chlorine contents of Bed, Weir Solids and elutriated materials assumed.
Other components of Bed, and Magnesia content of Weir Solids, interpolated from smoothed plots versus time.
Hydrogen content of primary cyclone solids assumed to be due to moisture absorbed after weighing, and the analysis has been corrected to the dry basis.

Table A.2.3.18 Mass Balances for Test 1.3

Test Series 1

Flow Rates in lb/h

	Total	Ash	Carbon	Hydrogen	Nitrogen	Oxygen
Inputs						
Coal	360	59.79	226.8	16.86	5	44.4
Dolomite	19	10.25	2.5	-	-	6.6
Main Air	3242	-	0.4	0.99	2482	758.9
Conveying Air	292	-	0.0	-	224	67.9
Dipleg Nitrogen	16	-	-	-	16	-
Total Input	3929	70.03	229.7	17.85	2728	877.7
Outputs						
Gained by Bed	-0	-1.00	0.2	-	-	0.6
Weir Solids	12	11.30	0.0	-	-	0.5
Primary Cyclone	72	61.77	4.9	-	-	3.1
Secondary Cyclone	1	0.92	0.1	-	-	0.1
Exhaust Dust	0	0.24	0.0	-	-	0.0
Flue Gas	3844	-	217.1	17.85	2705	899.7
Total Output	3929	73.23	222.2	17.85	2705	904.0
	Sulphur	Calcium	Magnesium	Sodium	Potassium	Chlorine
Inputs						
Coal	4.540	0.944	0.160	0.590	1.52	1.97
Dolomite	0.008	4.019	2.497	0.186	0.10	-
Main Air	-	-	-	-	-	-
Conveying Air	-	-	-	-	-	-
Dipleg Nitrogen	-	-	-	-	-	-
Total Input	4.548	4.963	2.657	0.775	1.61	1.97
Outputs						
Gained by Bed	0.226	0.345	0.233	0.048	0.05	-0.00
Weir Solids	0.317	0.592	0.331	0.163	0.30	0.01
Primary Cyclone	2.031	3.422	2.013	0.700	1.57	0.09
Secondary Cyclone	0.037	0.066	0.044	0.014	0.02	0.01
Exhaust Dust	0.010	0.013	0.016	0.005	0.01	0.00
Flue Gas	1.713	-	-	0.005	0.00	2.71
Total Output	4.333	4.438	2.637	0.934	1.95	2.83

Carbon Dioxide contents of Bed and Weir Solids assumed.
Chlorine contents of Bed, Weir Solids and Primary and Secondary Cyclone Solids assumed.
Other components of Bed interpolated from smoothed plots versus time.
Hydrogen content of Primary Cyclone Solids assumed to be due to Moisture absorbed after weighing, and the analysis has been corrected to the dry basis.

Table A.2.3.19 Mass Balances for Test 1.4

Test Series 1

Flow Rates in lb/h

	Total	Ash	Carbon	Hydrogen	Nitrogen	Oxygen
Inputs						
Coal	346	49.13	224.5	16.42	5	44.5
Dolomite	24	13.15	3.0	-	-	8.1
Main Air	3251	-	0.4	0.72	2491	759.2
Conveying Air	289	-	0.0	-	222	67.2
Dipleg Nitrogen	16	-	-	-	16	-
Total Input	3926	62.28	228.0	17.14	2733	878.9
Outputs						
Gained by Bed	-15	-16.79	0.1	-	-	1.0
Weir Solids	22	19.84	0.1	-	-	1.1
Primary Cyclone	77	64.92	5.0	-	-	4.4
Secondary Cyclone	1	0.57	0.0	-	-	0.0
Exhaust Dust	0	0.15	0.0	-	-	0.0
Flue Gas	3841	-	217.4	17.14	2693	911.0
Total Output	3926	68.69	222.6	17.14	2693	917.5

	Sulphur	Calcium	Magnesium	Sodium	Potassium	Chlorine
Inputs						
Coal	4.430	0.795	0.017	0.62	1.35	1.92
Dolomite	0.010	5.107	3.138	0.09	0.02	-
Main Air	-	-	-	-	-	-
Conveying Air	-	-	-	-	-	-
Dipleg Nitrogen	-	-	-	-	-	-
Total Input	4.440	5.902	3.155	0.71	1.37	1.92
Outputs						
Gained by Bed	0.720	2.364	1.360	0.29	-0.33	0.05
Weir Solids	0.661	1.402	0.759	0.32	0.54	0.03
Primary Cyclone	2.726	5.484	3.078	0.75	1.52	0.20
Secondary Cyclone	0.026	0.064	0.027	0.01	0.01	0.01
Exhaust Dust	0.006	0.010	0.017	0.00	0.00	0.00
Flue Gas	0.426	-	-	0.00	0.00	1.95
Total Output	4.566	9.325	5.240	1.38	1.74	2.24

Chlorine contents of Bed, Weir Solids and elutriated materials assumed. Other components of Bed interpolated from smoothed plots versus time. Hydrogen content of Primary Cyclone Solids assumed to be due to Moisture absorbed after weighing, and the analysis has been corrected to the dry basis.

Table A.2.3.19a Mass Balances for Test 1.5

Test Series 1

Flow Rates in lb/h

	Total	Ash	Carbon	Hydrogen	Nitrogen	Oxygen
Inputs						
Coal	319	39.04	213.1	15.52	4	40.8
Dolomite	24	13.11	3.0	-	-	8.1
Main Air	3286	-	0.4	0.87	2516	768.2
Conveying Air	283	-	0.0	-	218	65.8
Dipleg Nitrogen	15	-	-	-	16	-
Total Input	3928	52.15	216.5	16.39	2754	882.9
Outputs						
Gained by Bed	-14	-12.99	-0.1	-	-	- 0.3
Weir Solids	26	22.74	0.1	-	-	1.8
Primary Cyclone	56	46.62	3.1	-	-	3.8
Secondary Cyclone	1	0.59	0.0	-	-	0.0
Exhaust Dust	0	0.24	0.0	-	-	0.0
Flue Gas	3858	-	221.0	16.39	2715	903.7
Total Output	3928	57.20	224.2	16.39	2715	908.9

	Sulphur	Calcium	Magnesium	Sodium	Potassium	Chlorine
Inputs						
Coal	4.106	0.467	-0.105	0.680	1.13	1.75
Dolomite	0.010	5.093	3.128	0.090	0.02	-
Main Air	-	-	-	-	-	-
Conveying Air	-	-	-	-	-	-
Dipleg Nitrogen	-	-	-	-	-	-
Total Input	4.116	5.560	3.024	0.769	1.15	1.75
Outputs						
Gained by Bed	-0.150	-0.735	-0.033	-0.526	-0.59	0.03
Weir Solids	1.079	2.094	1.101	0.419	0.62	0.06
Primary Cyclone	2.382	4.620	2.702	0.652	1.06	0.26
Secondary Cyclone	0.028	0.066	0.047	0.014	0.01	0.01
Exhaust Dust	0.008	0.019	0.029	0.006	0.01	0.00
Flue Gas	0.596	-	-	0.003	0.02	1.40
Total Output	3.943	6.064	3.846	0.568	1.13	1.76

Hydrogen content of Primary Cyclone Solids assumed to be due to Moisture absorbed after weighing, and the analysis has been corrected to the dry basis.

Bed compositions interpolated from smoothed plots versus time.

Table A.2.3.20 Heat balances, million Btu/h

Test Series 1

Test No.	1.1	1.2	1.3	1.4	1.5
Heat Inputs					
In Coal-dolomite mixture, total	4.34	3.95	4.04	3.98	3.79
In Air and nitrogen, total	0.05	0.04	0.05	0.04	0.05
Heat of Sulphation of $CaCO_3$	0.00	0.01	0.01	0.02	0.02
Total Heat Input	4.39	4.00	4.10	4.04	3.86
Heat Outputs					
Weir solids, total	-	0.01	0.00	0.00	0.00
Elutriated solids, sensible	0.02	0.02	0.03	0.03	0.02
potential	0.12	0.09	0.08	0.07	0.05
Cyclone and weir blowdowns, total	0.05	0.05	0.05	0.05	0.05
Exhaust flue gas, sensible	1.23	1.17	1.24	1.19	1.19
potential	0.02	0.01	0.00	0.00	0.00
latent	0.18	0.16	0.16	0.16	0.15
To water cooling in bed	1.81	1.66	1.56	1.44	1.50
in freeboard	0.20	0.20	0.19	0.26	0.13
shell cooling	0.13	0.12	0.12	0.12	0.12
To shell pressurising air	0.02	0.02	0.01	0.02	0.02
Estimated radiation losses	0.01	0.01	0.01	0.01	0.01
Heat of calcination of $MgCO_3$	-	0.00	0.00	0.01	0.01
Total heat output	3.79	3.52	3.45	3.36	3.25
Unaccounted (input-output)	+0.60	+0.48	0.65	+0.68	+0.61
Unaccounted, % of input	+13.7	12.0	15.9	+16.8	+15.8

Total heats are the sums of sensible heat and of potential and/or latents heats.

Sensible heats refer to 32°F datum; the sensible heat of coal-acceptor mixture approx. 0.002 million Btu/h.

Potential heat of coal-acceptor mixture equals that of the coal fed.

Latent heat of water vapour in input gas approx. 0.02 millions Btu/h.

Total heat of weir solids includes that due to gain in weight of bed.

Reaction heats calculated assuming the following reaction equations:

$CaCO_3 + SO_2 + \frac{1}{2} O_2 = CaSO_4 + CO_2 + 77.1$ kcal/mole

$MgCO_3 = MgO + CO_2 - 24.2$ kcal/mole

Table A.2.3.21 Distribution of carbon loss in primary fines fractions

Test Series 1

Sample ref 1574
Sample time 4446 to 5407 mins

Grading	Wt %	% C in stated grade	lb C/100 lb sample	% of total C in stated grade
+ 1588µm	Nil			
-1588 + 794 µm	1.8	0.5	0.01	0.2
- 794 + 500 µm	7.6	0.4	0.03	0.5
- 500 + 251 µm	16.4	0.4	0.07	1.1
- 251 + 152 µm	12.7	0.3	0.04	0.6
- 152 + 75 µm	16.3	1.4	0.23	3.7
- 75 + 53 µm	7.4	6.0	0.44	7.1
- 53 µm	37.8	14.2	5.37	86.8
Total	100.0		6.19	100.0

Table A.2.3.22 Weight Losses of Corrosion Specimens $\mu g/cm^2h$

Test Series 1

Tube No.	Location of Ring	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t
1	Alloy	N		R	S	N	R	E	S	N	R	S	N	R	E		S	N	R	S	N
	Weight Loss	5	**	44	30	7	11	51	36	6	9	8	6	10	30	**	10	6	30	7	***
	Temperature (°F)		1450													1450					
2	Alloy	W		N	W	E	N	S	R	S	N	W	S	N	W		R	E	N	R	S
	Weight Loss	3	**	4	***	18	5	10	7	7	4	5	9	4	6	**	12	39	6	7	4
	Temperature (°F)		1330													1380					
3	Alloy	W		F_1	F_2	W	R	N	S	E	W	N	S	R	F_1		F_2	N	S	E	R
	Weight Loss	1	**	***	***	3	3	3	3	3	5	***	4	3	357	**	308	3	5	7	5
	Temperature (°F)		1020													1160					
4	Alloy	E		F_1	F_2	W	N	R	S	W	R	N	W	S	F_1		F_2	R	S	N	R
	Weight Loss	9	**	359	433	***	5	12	10	6	12	6	7	11	388	**	458	13	11	6	17
	Temperature (°F)		930													U/S					
5	Alloy	W		F_1	F_2	R	W	N	S	R	W	S	E	N	W		R	S	N	S	W
	Weight Loss	2.7	**	24	35	4	1	2	1	3	2	4	6	3	1	**	4	5	4	5	2
	Temperature (°F)		660													1020					
6	Alloy	N		R	S	N	R	E	S	N	R	S	N	R	E		S	N	R	S	N
	Weight Loss	7	**	13	***	8	13	49	13	9	10	12	9	***	68	**	15	13	13	12	11
	Temperature (°F)		1450													1450					

** Specimen used for measuring metal temperature
*** Specimen not descaled, retained for further examination.

F_1 Ferritic 1% Cr ½%Mo steel
F_2 Ferritic 2¼%Cr steel
W Ferritic 12%Cr steel

S Austenitic Type 316
R Austenitic Type 347
E Austenitic Type Esshete 1250
N Nimonic PE 16

Table A.2.3.23 Summary of weight losses of corrosion specimens

Test Series 1

Material		Tube 1		Tube 6		Tube 2		Tube 3		Tube 4		Tube 5	
		1450°F	1450°F	1450°F	1450°F	1330°F	1330°F	1160°F	1020°F	*	930°F	1020°F	660°F
1% Cr	Av. loss	-	-	-	-	-	-	357	-	388	359	-	24
	Max/Min	-	-	-	-	-	-	-	-	-	-	-	-
	No. of Specimens	-	-	-	-	-	-	1	-	1	1	-	1
2¼% Cr	Av. loss	-	-	-	-	-	-	307	-	458	433	-	35
	Max/Min	-	-	-	-	-	-	-	-	-	-	-	-
	No. of Specimens	-	-	-	-	-	-	1		1	1		1
12% Cr	Av. loss	-	-	-	-	6	3	5	3	7	-	2	2
	Max/Min	-	-	-	-	6/5	-	-	4/1	7/6	-	2/1	3/1
	No. of Specimens	-	-	-	-	2	1	1	2	2	-	3	2
SF316	Av. loss	33	8	13	13	7	10	5	3	11	10	5	1
	Max/Min	36/30	10/7	-	15/12	9/4	-	5/4	-	11/11	-	5/4	-
	No. of Specimens	2	3	1	3	3	1	2	1	2	1	2	1
RF36	Av. loss	27	15	13	12	9	7	4	3	14	12	4	4
	Max/Min	44/11	29/9	13/13	13/10	12/7	-	5/3	-	17/12	-	4/3	-
	No. of Specimens	2	3	2	2	2	1	2	1	3	1	2	1
Esshete 1250	Av. loss	51	30	49	68	39	18	7	3	-	9	6	-
	Max/Min	-	-	-	-	-	-	-	-	-	-	-	-
	No. of Specimens	1	1	1	1	1	1	1	1	-	1	1	-
PE 16	Av. loss	6	6	8	10	5	5	3	3	6	5	4	2
	Max/Min	6/6	7/5	8/7	13/9	6/4	5/4	-	-	6/6	-	4/3	-
	No. of Specimens	2	2	2	4	3	2	1	1	2	1	2	1

Notes:- (1) Under each Tube heading are given the measured metal temperatures at the outlet and inlet of each tube respectively.

(2) The "av. loss" and 'max/min" are the weight losses in $\mu g/cm^2h$.

* This thermocouple failed during the test. Comparison with other tests suggests that a probable temperature was 1020 to 1110°F.

Table A.2.3.24 Test Series 1 Metallographic examination of corrosion specimens

Temp. °F	Material	Surface Texture	Deposit Scale	Penetration µm	
				Pits	Sulphur
1110	F1 F2	v. rough v. rough	heavy heavy	0 0	0 0
1350	W	smooth	slight	0	0
1470	S R E N	smooth smooth rough smooth	slight slight slight slight	0 0 10 0	0 0 0 0

CLASSIFICATION OF SURFACE TEXTURE AS USED IN TABLES 3.24, 3.52, 3.85 & 3.113

The surface texture of the specimens after test, when examined metallographically, have been placed into one of three categories -

1. Smooth : surface irregularities of up to 4 µm
2. Rough : surface irregularities of up to 12 µm
3. Very rough : surface irregularities of greater than 12 µm

Irregularities of greater magnitude than the average texture have been reported as pits of specified depth.

Table A.2.3.25 Operating conditions during Test Series 2

Coal	Pittsburgh	
Coal size (upper limit)	1587	μm
Acceptor	Dolomite	1337
Acceptor size (upper limit)	1587	μm
Fluidising velocity	1.9	ft/s
Bed temperature	1465	°F
Bed height	3.75	ft

Test No.		2.1	2.2	2.3	2.4	2.5
Elapsed time from start of test series	Start, h	1.73	16.2	38.4	68.0	74.5
	End, h	15.2	37.2	67.1	72.5	80.5
Stoichiometric ratio		1.41	1.88	1.93	1.88	1.55
Coal rate	lb/h	420	420	420	500	420
Combustor pressure	atm.abs.	3.5	3.5	3.5	5	3.5

Table A.2.3.26 Analysis of spot samples of (coal + dolomite)

Test Series 2

Sample Ref	Sample time min	Moisture %	"Ash" %	CO_2 %	Size grading: % within stated size -1588 +794 μm	-794 +500 μm	-500 +251 μm	-251 +152 μm	-152 +75 μm	-75 μm	Median diameter μm
1	0	2.7	22.6	4.1	19	21	32	11	7	10	430
2	134	-	-	6.7	14	13	22	15	16	20	250
3	313	-	-	11.5	24	19	22	11	10	14	410
4	544	-	-	10.4	21	17	22	13	12	15	360
5	752	-	-	10.6	17	13	22	15	15	18	270
6	859	-	-	11.0	27	20	22	11	9	11	460
7	993	-	-	7.1	16	15	24	14	13	18	290
8	1216	-	-	13.8	33	19	19	9	9	11	530
9	1380	-	-	11.5	25	16	22	12	11	14	400
10	1564	-	-	16.9	33	17	20	11	10	9	500
11	1736	-	-	9.2	12	13	21	14	14	20	270
12	1919	-	-	10.1	18	14	21	14	15	18	280
13	2106	1.4	22.9	10.2	0	34	21	13	14	18	300
14	2326	1.0	25.2	12.2	27	16	19	12	12	14	400
15	2510	1.1	20.5	8.3	18	14	19	13	15	21	260
16	2683	0.9	20.9	10.0	20	14	19	12	14	21	280
17	2878	1.0	24.0	10.3	23	15	20	13	13	16	340
18	3102	-	-	9.4	20	16	23	13	11	17	330
19	3282	-	-	16.8	34	18	18	10	9	11	520
20	3475	-	-	10.5	19	13	21	14	13	20	280
21	3676	-	-	10.3	21	14	19	12	15	19	290
22	3832	-	-	12.9	24	16	18	11	12	19	350
23	4002	-	-	11.1	26	17	20	11	11	15	450
24	4182	-	-	8.9	38	19	19	9	7	8	640
25	4363	-	-	14.7	22	17	20	12	12	17	400
26	4596	-	-	10.0	30	18	18	9	9	16	500
27	4732	-	-	7.1	20	15	20	12	13	20	310
28	4806	-	-	10.1	27	18	17	10	10	18	510
29	4890	-	-	7.7	21	17	21	12	11	18	460

Analyses are given as weight percent on an 'as fired' basis.

Table A.2.3.27 Analysis of bulked samples of (coal + dolomite)

Test Series 2

Test		2.1	2.2	2.3	2.4	2.5
Sample Ref		1599	1600	1601	1602	1603
Total moisture	%	1.7	1.2	1.2	1.3	1.4
Carbon dioxide	%	9.6	11.3	11.3	11.6	9.3
Ash	%	22.2	24.3	23.5	22.6	19.7
Carbon	%	61.6	57.1	58.6	59.1	63.6
Hydrogen	%	3.9	3.4	3.5	3.6	4.0
Nitrogen	%	0.6	0.6	0.9	1.0	0.6
Sulphur	%	2.6	2.3	2.2	2.2	2.2
Oxygen + errors	%	9.1	12.2	11.2	11.4	9.8
Chlorine	%	0.05	0.08	0.07	0.07	0.09
Ash analysis						
CaO	%	32.7	34.2	34.7	35.2	34.0
MgO	%	18.9	20.7	22.6	23.4	21.8
Na_2O	%	0.3	0.5	0.5	0.4	0.5
K_2O	%	0.7	0.8	0.7	0.6	0.7
Ash fusion (in air)						
Initial deformation,	°F	-	2480	2515	2480	2515
Hemisphere	°F	-	2535	2535	2535	2535
Flow	°F	-	-	-	-	-

Analyses are given on a weight percent basis.
Total moisture and carbon dioxide are given on an 'as received' basis.
Ultimate analysis is given on a dry basis.

Table A.2.3.28 Analysis of (coal + dolomite): overall sample

Test Series 2

Sample Ref.		1604
Proximate analysis		
Moisture	%	1.3
Ash	%	23.1
Volatile matter	%	49.5
Fixed carbon	%	38.1
Swelling number		6
Gray King coke type		G7
Forms of sulphur		
Pyritic	%	1.38
Sulphatic	%	0.06
Organic	%	0.82
Total	%	2.26
Ash analysis		
SiO_2	%	20.8
Al_2O_3	%	9.2
Fe_2O_3	%	7.0
CaO	%	33.5
MgO	%	21.0
Na_2O	%	0.5
K_2O	%	0.8
TiO_2	%	0.4
Mn_3O_4	%	0.1
P_2O_5	%	0.2
SO_3	%	4.6
Total	%	98.1

Except for volatile matter, the analyses are given on an 'as received' basis; volatile matter is given on a d.a.f. basis.

Table A.2.3.29 Analysis of Dolomite

Test Series 2

Material		Raw Dolomite*	Sieved Dolomite **
Sample ref		1591	1647
Moisture	%	-	0.1
Loss on ignition at 800°C	%	-	44.3
SiO_2	%	-	0.7
Al_2O_3	%	-	<0.1
Fe_2O_3	%	-	0.2
CaO	%	-	31.0
MgO	%	-	21.4
Na_2O	%	-	0.1
K_2O	%	-	0.1
S	%	-	<0.05
CO_2	%	-	47.6
Size grading		% within stated size	
-2411 +1588 μm		22	0
-1588 + 794 μm		71	75
- 794 + 500 μm		6	18
- 500 + 0 μm		1	7
Median diameter μm		1390	1100
Mean diameter, D_p, μm		1060	700

Analyses are on a weight per cent basis

* Before sieving

** As blended with coal fed to the combustor

D_p as defined in Table A.2.3.8.

Table A.2.3.30 Chemical analysis and size grading of shale + coal mixture

Test Series 2

Test Series Sample Ref		2 1620
Carbon		10.0
Sulphur		0.3
Chlorine		0.06
CaO		3.3
MgO		2.9
Na_2O		0.5
K_2O		3.2
Size grading		
% within stated size grade		
-1588 +794	μm	24
-794 +500	μm	47
-500 +251	μm	23
-251 +152	μm	2
-152 + 75	μm	1
- 75 + 0	μm	3
Median diameter	μm	650
Mean diameter, D_p	μm	370

Analyses are given as weight per cent on an 'as received' basis.

Dp as defined in Table A.2.3.8.

Test Series 2

Test		2.1	2.2	2.3	2.4	2.5
Sample Ref		1605	1606	1607	1608	1609
Carbon	%	4.5	9.2	11.1	10.0	22.0
Hydrogen	%	0.1	0.1	0.1	0.1	0.2
Sulphur	%	3.5	3.9	4.3	4.4	2.8
Carbon dioxide	%	5.0	8.3	8.6	5.5	5.4
Chlorine	%	0.16	0.05	0.07	0.08	0.06
CaO	%	13.7	17.7	18.9	16.4	13.5
MgO	%	4.9	8.4	5.6	7.4	7.2
Na_2O	%	0.6	0.4	0.3	0.4	0.4
K_2O	%	1.7	0.9	0.6	0.8	0.7
Size Grading		% within stated size grade				
-1588+794 µm		16	7	6	3	-
- 794+500 µm		21	11	7	4	1
- 500+251 µm		24	11	7	3	2
- 251-152 µm		9	7	4	2	2
- 152+ 75 µm		7	12	11	5	6
- 75+ 0 µm		23	52	65	83	89
Median diameter µm		360	70	45	25	35
Mean diameter D_p µm		120	65	55	45	40

Analyses are given as weight percent on an 'as received' basis.
% carbon does not include carbon present as carbon dioxide.

[illegible] Analyses of Secondary Cyclone Fines

Test Series 2

Test		2.1	2.2	2.3	2.4	2.5
Sample Ref		1610	1611	1612	1613	1614
Carbon	%	3.7	3.3	3.9	1.9	2.4
Hydrogen	%	0.1	0.1	0.1	0.1	0.1
Sulphur	%	3.4	2.7	2.9	3.2	2.5
Carbon dioxide	%	1.7	0.5	0.7	0.4	0.6
Chlorine	%	0.11	0.09	0.08	0.08	0.09
CaO	%	9.7	8.6	9.2	9.2	8.7
MgO	%	6.4	5.6	5.0	5.2	5.3
Na_2O	%	0.8	0.7	0.7	0.7	0.6
K_2O	%	1.8	1.6	1.6	1.6	1.5
Size Grading		% within stated size grade				
- 75 + 60 μm		1	-	2	1	1
- 60 + 50 μm		8	-	5	2	3
- 50 + 40 μm		11	1	6	5	3
- 40 + 30 μm		11	2	1	4	1
- 30 + 20 μm		11	5	5	9	9
- 20 + 10 μm		19	21	16	27	23
- 10 + 5 μm		23	51	36	27	39
- 5 + 0 μm		16	20	29	24	21
Median diameter μm		30	7	7	10	8
Mean diameter, D_p μm		12	6	6	7	7

Analyses are given as weight percent on an 'as received' basis.

% Carbon does not include carbon present as carbon dioxide.

Size gradings were obtained by a Coulter Count on the material passing through a 75 micron sieve. For sample ref: 1610, 26% was + 75 micron. The remaining samples were 100% less than 75 micron.

Table A.2.3.33 Analysis of Exhaust Dust

Test Series 2

Test	2.1	2.2	2.3	2.4	2.5
Sample Ref	1615	1616	1617	1618	1619
Carbon %	3.1	2.7	3.9	2.2	7.0
Hydrogen %	0.2	0.2	0.1	0.2	0.2
Sulphur %	3.3	4.1	3.3	4.4	3.2
Carbon dioxide %	0.2	0.5	0.5	0.4	0.5
Chlorine %	0.2	0.2	0.1	0.3	0.3
CaO %	7.7	9.0	10.5	10.4	10.0
MgO %	7.6	6.5	5.4	5.2	4.5
Na_2O %	1.0	0.8	0.7	0.8	0.8
K_2O %	1.9	1.6	1.7	1.8	1.8
Size Grading	% within stated size range				
-75 +60 µm	8	2	1	-	1
-60 +50 µm	3	1	1	-	2
-50 +40 µm	5	2	0	4	0
-40 +30 µm	6	6	1	3	7
-30 +20 µm	6	8	7	8	8
-20 +10 µm	12	16	14	25	15
-10 + 5 µm	23	26	33	31	30
- 5 + 0 µm	36	39	43	29	37
Median diameter, µm	7	6	6	8	6
Mean diameter, D_p µm	6	5	5	6	5

Chemical analyses are given as weight percent, on an 'as received' basis.

% Carbon does not include carbon present as carbon dioxide.

Table A.2.3.34 Analysis of bulked samples of bed material

Test Series 2

Test		Before 2.1	2.1	2.2	2.3	2.4	2.5	After 2.5
Sample ref		1589	1622	1621	1643	1644	1645	1642
Carbon	%	0.1	0.1	0.2	0.2	0.1	0.1	-
Sulphur	%	2.6	4.1	8.3	7.9	8.1	8.8	9.2
Carbon dioxide	%	0.4	6.4	10.4	11.7	11.3	10.3	-
Chlorine	%	0.14	0.05	0.06	0.05	0.05	0.04	-
CaO	%	7.3	16.8	32.8	31.2	32.2	33.2	31.5
MgO	%	5.5	11.9	21.9	21.4	22.7	21.8	21.2
Na_2O	%	1.4	0.7	0.4	0.3	0.9	0.7	-
K_2O	%	2.6	1.7	0.6	0.4	0.7	0.6	-
Sulphite sulphur	%	-	0.03	0.02	-	-	-	-
Sulphide sulphur	%	-	<0.01	<0.01	-	-	-	-
Size grading		% within stated size grade						
-1588 + 794	µm	15	29	51	63	59	56	52
- 794 + 500	µm	30	27	25	23	24	24	25
- 500 + 251	µm	44	36	18	11	14	16	19
- 251 + 152	µm	10	8	6	3	3	4	4
- 152 + 0	µm	1	0	0	0	0	0	0
Median diameter	µm	475	550	810	950	910	880	420
Mean diameter, D_p,	µm	400	470	590	710	670	650	350

Analyses are given as weight percent on an 'as received' basis

% Carbon does not include carbon present as carbon dioxide

Sulphur not present as sulphite or sulphide is assumed to be present as sulphate

Samples 1621, 1622, 1643-1645 refer to bed material extracted during the test via the weir.

D_p as defined in Table A.2.3.8.

Table A.2.3.35 Analysis of additional samples of bed material extracted via the weir

Test Series 2

Sample Ref	1622	1623	1624	1625	1626	1627	1628	1629	1630	1631	
Sample time, min	909 to 924	1493 to 1589	1763 to 1810	2235	2617 to 2665	2793 to 3807	2916 to 2930	3040 to 3048	3152 to 3163	3261 to 3270	
CaO	16.8	33.1	32.5	28.4	30.5	30.2	29.7	30.2	31.0	30.5	
MgO	11.9	23.5	20.2	18.3	21.5	21.0	20.6	20.6	21.1	20.9	
Sulphur	4.1	8.7	7.8	7.0	7.5	7.7	7.6	7.7	7.9	8.0	
Size Grading	% within stated size grade										
- 1588 + 794 μm	29	58	58	45	60	50	58	57	52	53	
- 794 + 500 μm	27	29	23	27	14	26	25	24	25	26	
- 500 + 251 μm	36	10	15	21	13	18	14	15	18	16	
- 251 + 152 μm	8	3	4	7	3	5	3	4	5	5	
- 152 + 75 μm	0	0	0	0	0	1	0	0	0	0	
Median size μm	560	900	890	740	920	800	890	890	820	840	
Mean dia. D_p, μm	470	670	650	550	680	590	670	650	600	610	
Sample Ref	1632	1633	1634	1635	1636	1637	1638	1639	1640	1641	1642
Sample time, min	3391 to 3406	3521 to 3536	3641 to 3656	3750 to 3765	3891 to 3906	3992 to 4000	4111 to 4120	4355 to 4363	4541 to 4556	4687 to 4702	4890
CaO	31.4	30.7	34.1	32.6	33.1	32.1	32.2	32.8	33.5	32.8	31.5
MgO	21.6	20.9	22.7	22.8	23.0	22.0	22.7	23.2	21.7	21.9	21.2
Sulphur	8.0	8.1	8.1	8.1	7.7	8.1	8.1	8.3	8.7	8.9	9.2
Size Grading	% within stated size grade										
- 1588 + 794 μm	65	62	71	63	57	65	60	60	57	60	52
- 794 + 500 μm	22	22	21	24	24	23	24	24	24	24	25
- 500 + 251 μm	11	13	7	11	15	10	13	13	16	13	19
- 250 + 152 μm	2	3	1	2	4	2	3	3	3	3	2
- 152 + 75 μm	0	0	0	0	0	0	0	0	0	0	0
Median size μm	990	940	1040	960	890	980	920	910	880	930	820
Mean dia. D_p, μm	740	690	810	730	660	730	670	670	650	700	610

Analyses are given as weight percent on an 'as received' basis.

D_p as defined in Table A.2.3.8.

Table A.2.3.36 Gas composition measurements

Test Series 2

Test No.		2.1	2.2	2.3	2.4	2.5
Elapsed time from start of Test Series	Start, h	1.73	16.2	38.4	68.0	74.5
	End, h	15.2	37.2	67.1	72.5	80.5
Operating conditions	Ca/S mol ratio	1.41	1.88	1.93	1.88	1.55
	Variable parameter	Pressure 3½ atm	Pressure 3½ atm	Pressure 3½ atm	Pressure 5 atm	Pressure 3½ atm
Gas composition % by volume (dry gas)	CO_2	15.4	14.8	14.8	13.8	15.4
	CO	0.03	0.03	0.04	0.02	0.06
	O_2	3.0	4.5	4.9	6.3	3.8
Gas composition p.p.m. by volume (dry gas)	SO_2	210	90	70	110	220
	SO_3	1	0	1	-	0
	NO_x	80	130	90	100	70
	Cl	80	70	50	-	-
	Na_2O	0.9	0.5	0.3	-	-
	K_2O	0.3	0.2	0.1	-	-

Table A.2.3.37 Variation in gas composition

Test Series 2

Oxygen in combustion products (volume basis)

Test	% of test time in stated range					mean oxygen %
	< 1%	1-2%	2-4%	4-6%	> 6%	
2.1	8	26	45	17	4	2.98
2.2	5	5	36	33	21	4.51
2.3	1	4	24	48	23	4.94
2.4	0	0	12	29	59	6.34
2.5	3	17	39	33	8	3.81

Carbon monoxide in combustion products (volume basis)

Test	% of test time in stated range			mean CO %
	0 to 0.025%	0.025 to 0.05%	> 0.05%	
2.1	92	0	8	0.030
2.2	94	2	4	0.029
2.3	94	3	3	0.037
2.4	59	41	0	0.023
2.5	57	26	17	0.064

Table A.2.3.38 Variation of temperature in bed and freeboard

Test Series 2

Height above distributor*	Test	% of test time in stated temperature ranges					Mean temp. °F
		<1400°F	1400° to 1436°	1436° to 1472°F	1472° to 1508°F	>1508°F	
Bed 1 in to 5 in	2.1	6	35	39	18	2	1445
	2.2	6	35	45	13	1	1443
	2.3	3	30	52	14	1	1449
	2.4	7	34	48	10	1	1443
	2.5	4	33	49	13	1	1443
Bed 13 in to 16 in	2.1	4	24	43	26	3	1454
	2.2	2	23	46	25	4	1456
	2.3	1	12	45	37	5	1467
	2.4	0	18	42	34	6	1463
	2.5	1	16	39	39	5	1463
Bed 36 in	2.1	0	7	36	47	10	1474
	2.2	0	3	35	50	12	1481
	2.3	0	0	17	65	18	1490
	2.4	2	0	19	46	33	1488
	2.5	0	2	12	68	18	1490
Freeboard 77 in	2.1	1	7	34	47	11	1477
	2.2	8	11	32	16	33	1479
	2.3	16	23	35	15	11	1449
	2.4	0	6	18	27	49	1506
	2.5	0	0	6	26	68	1517
Freeboard 107	2.1	8	49	27	15	1	1434
	2.2	19	54	26	1	0	1418
	2.3	0	21	38	36	1	1427
	2.4	48	28	21	3	0	1409
	2.5	61	21	14	3	1	1393

Table A.2.3.39 Measurements of SO_2 and SO_3 in exhaust gases

Test Series 2

Time from start, min	SO_2 p.p.m. (v/v)	SO_3 p.p.m. (v/v)	Time from start, min	SO_2 p.p.m. (v/v)	SO_3 p.p.m. (v/v)
186	297	0	2382	75	1.0
242	241	2.3	2463	68	0
303	285	0	2530	65	0.7
434	346	0	2673	70	1.3
527	223	0	2751	73	0.7
635	135	0.7	2983	65	0
759	88	0	3050	84	0.3
892	100	1.8	3210	76	0
1001	92	1.4	3318	124	0
1070	167	0	3426	101	0
1126	81	0	3626	54	0.9
1268	83	0.5	3720	72	0.5
1348	68	1.0	3917	53	0
1398	84	0.6	3968	56	0
1488	77	0.5	4127	93	0
1573	35	0	4187	96	0
1663	55	0.5	4281	133	0
1733	43	0	4360	252	-
1793	54	0.3	4485	107	0.5
1833	37	0	4572	262	0.5
1894	44	0.3	4675	221	0
1948	88	0	4760	270	0
2084	102	0	4810	220	0.2
2214	65	2.0	4860	401	0
2335	43	1.0			

Table A.2.3.40 Percentage Retention of Sulphur, Alkalis and Chlorine

Test Series 2

Test No.	2.1	2.2	2.3	2.4	2.5
Stoichiometric ratio	1.41	1.88	1.93	1.88	1.55
Total Ca/S Mole ratio	1.57	2.04	2.09	2.04	1.71
Per cent retention					
Sulphur	92.3	96.4	96.8	94.5	90.6
Sodium	98.8	99.3	99.5	99.2	99.4
Potassium	99.8	99.7	99.8	99.7	99.8
Chlorine	32.6	20.5	28.2	22.0	24.7
Per cent reduction					
Sulphur emission	89.4	95.6	96.4	94.7	89.4

% Retention of sulphur, sodium and potassium
= 100 (Total input-output in gas)/Total input

% Retention of chlorine
= 100 (Total output-output in gas)/Total output

% Reduction of sulphur emission
= 100 (Emission without acceptor - Emission observed)/(Emission without acceptor)

Emission without acceptor assumed to be 2032 ppm v/v in dry gas

Stoichiometric ratio assumed = (Total Ca/S mole ratio - 0.16)

For Test 2.1, the stoichiometric ratio and total Ca/S mole ratio do not take into account calcium and sulphur inputs in the shale-coal mixture. If these are taken into account, stoichiometric ratio = 1.29 and total Ca/S mole ratio = 1.64.

Table A.2.3.41 Concentration of NO_x in combustion gases

Test Series 2

Time from start, min	NO_x p.p.m. (v/v)	Method
286 to 290	77 to 79	Hersch
293	92	Saltzman
294	103	"
295 to 297	68 to 73	Hersch
301	122	Saltzman
303 to 310	71 to 88	Hersch
884	93	"
988	150	"
1098	99	"
1108	73	"
1338 to 1348	93 to 113	"
1348 to 1358	104 to 120	"
1358 to 1368	106 to 129	"
1368 to 1378	115 to 131	"
1378 to 1386	113 to 127	"
1630 to 1640	115 to 134	"
1640 to 1650	110 to 134	"
1650 to 1660	122 to 136	"
1660 to 1670	124 to 134	"
1670 to 1680	124 to 139	"
2029 to 2046	81 to 111	"
2061 to 2064	93 to 97	"
2069 to 2089	93 to 120	"
2384 to 2393	62 to 82	"
2397 to 2401	93 to 111	"
2404 to 2412	88 to 102	"
2418 to 2426	88 to 111	"
2428 to 2437	88 to 120	"
2067 to 3079	69 to 93	"
3447	77	"
3478	66	"
3479	68	"
3484	84	Hersch
3485	77	"
3486	82	"
3487	82	"
3772	84	"
3773	86	"
3775	88	"
3776	97	"
3777	84	"
3778	79	"
3779	93	"
3780	89	"
3781	79	"
3782	84	"
3946	120	"
3947	115	"
3948	95	"
3949	88	"
3950	84	"
3951	88	"
3952	93	"
3954	97	"
3955	111	"
3956	97	"
3957	93	"
3958	95	"
3959	95	"
3960	95	"
3961	93	"
4720 to 4722	63 to 79	"
4727 to 4734	63 to 82	"

Table A.2.3.42 Determinations of Alkalis and Chlorine in Flue Gas

Test Series 2

Time, from start, h	Concentration, µg/l dry gas			Concentration, ppm by volume, dry gas		
	C_1	Na_2O	K_2O	Cl	Na_2O	K_2O
5.33	123	2.6	1.3	78	1.0	0.3
23.42	110	1.3	0.9	70	0.5	0.2
27.48	110	1.3	0.9	70	0.5	0.2
50.53	79	0.9	0.4	50	0.3	0.1

Table A.2.3.43 Mass Balances for Test 2.1

Test Series 2

Flow Rates in lb/h

	Total	Ash	Carbon	Hydrogen	Nitrogen	Oxygen
Inputs						
Coal	331	44.2	237.8	16.35	2	19.7
Dolomite	79	41.1	10.2	0.01	-	27.3
Shale + Coal	56	49.1	5.6	0.40	0	0.5
Main Air	3204	-	0.4	0.85	2454	748.8
Conveying Air	307	-	0.0	-	236	71.4
Dipleg Nitrogen	31	-	-	-	31	-
Total Input	4009	134.4	254.1	17.61	2724	867.7
Outputs						
Gained by Bed	15	0.8	2.3	-	-	9.8
Primary Cyclone	146	119.0	8.5	-	-	13.1
Secondary Cyclone	3	2.5	0.1	-	-	0.2
Exhaust Dust	1	0.6	0.0	-	-	0.0
Flue Gas	3844	-	222.2	17.61	2756	846.5
Total Output	4009	122.8	233.1	17.61	2756	869.6

	Sulphur	Calcium	Magnesium	Sodium	Potassium	Chlorine
Inputs						
Coal	10.64	3.46	0.04	0.141	0.45	0.205
Dolomite	0.02	17.43	10.15	0.058	0.07	-
Shale + Coal	0.17	1.33	0.98	0.219	1.47	0.034
Main Air	-	-	-	-	-	-
Conveying Air	-	-	-	-	-	-
Dipleg Nitrogen	-	-	-	-	-	-
Total Input	10.83	22.22	11.17	0.417	1.99	0.239
Outputs						
Gained by Bed	2.45	9.90	5.71	-0.479	-0.62	-0.080
Primary Cyclone	5.16	14.42	4.35	0.656	2.08	0.236
Secondary Cyclone	0.10	0.20	0.11	0.017	0.04	0.003
Exhaust Dust	0.02	0.04	0.03	0.005	0.01	0.001
Flue Gas	0.83	-	-	0.005	0.00	0.331
Total Output	8.55	24.56	10.21	0.204	1.52	0.491

Sulphate content of "Ash" of Coal-Dolomite mixture assumed constant throughout Test Series 2.
Bed compositions interpolated from smoothed plots versus time.
Hydrogen contents of elutriated solids assumed to be due to moisture absorbed after weighing, and the analyses have been corrected to the dry basis.

Table A.2.3.44 Mass Balances for Test 2.2

Test Series 2

Flow Rates in lb/h

	Total	Ash	Carbon	Hydrogen	Nitrogen	Oxygen
Inputs						
Coal	321	45.83	221.9	15.11	2	26.2
Dolomite	95	49.42	12.3	0.01	-	32.8
Main Air	3239	-	0.4	0.68	2482	755.9
Conveying Air	267	-	0.0	-	205	62.0
Dipleg Nitrogen	17	-	-	-	17	-
Total Input	3939	95.25	234.6	15.80	2706	876.9
Outputs						
Gained by Bed	13	-2.31	1.4	-	-	9.8
Weir Solids	33	22.44	1.0	-	-	6.5
Primary Cyclone	73	52.87	8.5	-	-	8.7
Secondary Cyclone	1	1.29	0.0	-	-	0.1
Exhaust Dust	1	0.94	0.0	-	-	0.1
Flue Gas	3818	-	213.5	15.80	2721	867.0
Total Output	3939	75.22	224.4	15.80	2721	892.2

	Sulphur	Calcium	Magnesium	Sodium	Potassium	Chlorine
Inputs						
Coal	9.55	3.45	0.26	0.300	0.585	0.333
Dolomite	0.02	20.95	12.21	0.070	0.079	-
Main Air	-	-	-	-	-	-
Conveying Air	-	-	-	-	-	-
Dipleg Nitrogen	-	-	-	-	-	-
Total Input	9.57	24.40	12.47	0.370	0.663	0.333
Outputs						
Gained by Bed	4.27	11.46	6.16	-0.148	-0.687	0.016
Weir Solids	2.71	7.66	4.32	0.097	0.163	0.020
Primary Cyclone	2.87	9.32	3.73	0.219	0.550	0.037
Secondary Cyclone	0.04	0.09	0.05	0.008	0.019	0.001
Exhaust Dust	0.05	0.07	0.04	0.007	0.015	0.002
Flue Gas	0.34	-	-	0.003	0.002	0.295
Total Output	10.28	28.60	14.30	0.184	0.062	0.371

Sulphate content of "Ash" of Coal-Dolomite mixture assumed constant throughout Test Series 2.
Bed compositions interpolated from smoothed plots versus time.
Hydrogen contents of elutriated solids assumed to be due to moisture absorbed after weighing, and the analyses have been corrected to the dry basis.

Table A.2.3.45 Mass Balances for Test 2.3

Test Series 2

Flow Rates in lb/h

	Total	Ash	Carbon	Hydrogen	Nitrogen	Oxygen
Inputs						
Coal	323	42.7	229.2	15.18	4	22.3
Dolomite	95	49.8	12.4	0.01	-	33.1
Main Air	3454	-	0.4	0.72	2647	806.0
Conveying Air	276	-	0.0	-	212	64.1
Dipleg Nitrogen	17	-	-	-	17	-
Total Input	4165	92.5	242.1	15.91	2879	925.6
Outputs						
Gained by Bed	1	0.6	0.3	-	-	0.6
Weir Solids	65	44.3	2.2	-	-	13.2
Primary Cyclone	82	56.8	11.1	-	-	10.5
Secondary Cyclone	2	1.4	0.1	-	-	0.1
Exhaust Dust	1	0.7	0.0	-	-	0.0
Flue Gas	4014	-	224.3	15.91	2851	922.9
Total Output	4165	103.8	237.9	15.91	2851	947.3
	Sulphur	Calcium	Magnesium	Sodium	Potassium	Chlorine
Inputs						
Coal	9.177	2.93	0.91	0.289	0.484	0.293
Dolomite	0.019	21.12	12.31	0.071	0.079	-
Main Air	-	-	-	-	-	-
Conveying Air	-	-	-	-	-	-
Dipleg Nitrogen	-	-	-	-	-	-
Total Input	9.196	24.05	13.22	0.360	0.564	0.293
Outputs						
Gained by Bed	-0.053	0.13	0.50	0.194	0.054	-0.005
Weir Solids	5.119	14.45	8.36	0.144	0.215	0.032
Primary Cyclone	3.558	11.18	2.79	0.184	0.412	0.058
Secondary Cyclone	0.047	0.11	0.05	0.008	0.021	0.001
Exhaust Dust	0.028	0.06	0.03	0.004	0.012	0.001
Flue Gas	0.293	-	-	0.002	0.001	0.223
Total Output	8.991	25.92	11.73	0.537	0.715	0.311

Sulphate content of "Ash" of Coal-Dolomite mixture assumed constant throughout Test Series 2.
Bed compositions interpolated from smoothed plots versus time.
Hydrogen contents of elutriated solids assumed to be due to moisture absorbed after weighing, and the analyses have been corrected to the dry basis.

Table A.2.3.46 Mass Balances for Test 2.4

Test Series 2

Flow Rates in lb/h

	Total	Ash	Carbon	Hydrogen	Nitrogen	Oxygen
Inputs						
Coal	383	44.9	276.8	18.75	5	26
Dolomite	118	61.7	15.3	0.01	-	41
Main Air	4797	-	8.2	-	3670	1120
Conveying Air	402	-	0.0	-	309	93
Dipleg Nitrogen	28	-	-	-	28	-
Total Input	5728	106.6	300.3	18.76	4011	1280
Outputs						
Gained by Bed	12	5.9	0.4	-	-	4
Weir Solids	33	22.7	1.1	-	-	7
Primary Cyclone	78	57.1	9.1	-	-	8
Secondary Cyclone	1	0.9	0.0	-	-	0
Exhaust Dust	1	0.6	0.0	-	-	0
Flue Gas	5603	-	293.9	18.76	3997	1293
Total Output	5728	87.2	304.4	18.76	3997	1312

	Sulphur	Calcium	Magnesium	Sodium	Potassium	Chlorine
Inputs						
Coal	11.00	1.96	0.54	0.244	0.459	0.351
Dolomite	0.02	26.14	15.23	0.088	0.098	-
Main Air	-	-	-	-	-	-
Conveying Air	-	-	-	-	-	-
Dipleg Nitrogen	-	-	-	-	-	-
Total Input	11.02	28.11	15.77	0.332	0.556	0.351
Outputs						
Gained by Bed	1.94	4.45	0.97	0.077	0.227	0.006
Weir Solids	2.69	7.64	4.55	0.222	0.193	0.017
Primary Cyclone	3.46	9.22	3.51	0.234	0.523	0.063
Secondary Cyclone	0.03	0.07	0.03	0.005	0.013	0.001
Exhaust Dust	0.03	0.05	0.02	0.004	0.011	0.002
Flue Gas	0.61	-	-	0.003	0.001	0.315
Total Output	8.77	21.43	9.09	0.544	0.968	0.403

Sulphate content of "Ash" of Coal-Dolomite mixture assumed constant throughout Test Series 2.

Bed compositions interpolated from smoothed plots versus time.

Hydrogen contents of elutriated solids assumed to be due to moisture absorbed after weighing, and the analyses have been corrected to the dry basis.

Table A.2.3.47 Mass Balances for Test 2.5

Test Series 2

Flow Rates in lb/h

	Total	Ash	Carbon	Hydrogen	Nitrogen	Oxygen
Inputs						
Coal	341	36.60	253.1	17.03	3	22.4
Dolomite	79	41.13	10.2	0.01	-	27.3
Main Air	3429	-	0.4	0.91	2627	801.4
Conveying Air	279	-	0.0	-	215	64.9
Dipleg Nitrogen	10	-	-	-	10	-
Total Input	4139	77.73	263.8	17.95	2854	916.0
Outputs						
Gained by Bed	-27	-19.89	-1.7	-	-	-5.1
Weir Solids	54	36.84	1.6	-	-	11.3
Primary Cyclone	95	61.75	22.6	-	-	7.9
Secondary Cyclone	2	1.29	0.1	-	-	0.1
Exhaust Dust	1	0.64	0.1	-	-	0.0
Flue Gas	4015	-	233.1	17.95	2846	915.9
Total Output	4139	80.63	255.8	17.95	2846	930.0

	Sulphur	Calcium	Magnesium	Sodium	Potassium	Chlorine
Inputs						
Coal	9.224	2.36	0.55	0.244	0.408	0.378
Dolomite	0.016	17.44	10.16	0.058	0.065	-
Main Air	-	-	-	-	-	-
Conveying Air	-	-	-	-	-	-
Dipleg Nitrogen	-	-	-	-	-	-
Total Input	9.240	19.80	10.71	0.302	0.473	0.378
Outputs						
Gained by Bed	-0.586	-8.29	-5.23	-0.592	-0.508	-0.011
Weir Solids	4.796	12.93	7.17	0.283	0.271	0.022
Primary Cyclone	2.708	9.33	4.20	0.287	0.562	0.058
Secondary Cyclone	0.039	0.10	0.05	0.007	0.019	0.001
Exhaust Dust	0.025	0.06	0.02	0.005	0.012	0.002
Flue Gas	0.868	-	-	0.002	0.001	0.222
Total Output	7.850	14.13	6.21	-0.008	0.357	0.294

Sulphate content of "Ash" of Coal Dolomite mixture assumed constant throughout Test Series 2.

Bed compositions interpolated from smoothed plots versus time.

Hydrogen contents of elutriated solids assumed to be due to moisture absorbed after weighing, and the analyses have been corrected to the dry basis.

Table A.2.3.48 Heat balances, million Btu/h

Test Series 2

Test No	2.1	2.2	2.3	2.4	2.5
Heat Inputs					
In coal-dolomite mixture, total	4.29	4.01	4.08	4.92	4.45
In shale-coal mixture, total	0.10	-	-	-	-
In air and nitrogen, total	0.04	0.04	0.04	0.06	0.05
Heat of Sulphation of $CaCO_3$	0.04	0.04	0.04	0.04	0.04
Total Heat Input	4.47	4.09	4.16	5.03	4.54
Heat Outputs					
Weir solids, total	0.01	0.02	0.03	0.02	0.01
Elutriated solids, sensible	0.05	0.03	0.03	0.03	0.03
potential	0.10	0.10	0.13	0.11	0.31
Cyclone and weir blowdowns, total	0.05	0.05	0.05	0.05	0.05
Exhaust flue gas, sensible	1.31	1.32	1.40	1.96	1.40
potential	0.00	0.00	0.01	0.00	0.01
latent	0.17	0.15	0.15	0.19	0.17
To water cooling, in bed	2.01	1.88	1.93	2.56	2.14
in freeboard	0.09	0.14	0.16	0.19	0.21
shell cooling	0.12	0.13	0.12	0.12	0.12
To shell pressurising air	0.01	0.01	0.01	0.02	0.02
Estimated radiation losses	0.01	0.01	0.01	0.01	0.01
Heat of calcination of $MgCO_3$	0.02	0.02	0.02	0.03	0.02
Total Heat Output	3.95	3.86	4.05	5.29	4.50
Unaccounted (Input-Output)	+0.52	+0.23	+0.11	-0.27	+0.04
Unaccounted, % of Input	+11.6	+5.6	+2.6	-5.4	+0.9

Total heats are the sums of sensible heat and of potential and/or latent heats.
Sensible heats refer to 32°F datum; the sensible heat of coal-acceptor mixture approx. 0.002 million Btu/h
Potential heat of coal-acceptor mixture equals that of the coal fed.
Latent heat of water vapour in input gas approx. 0.02 million Btu/h.
Total heat of weir solids includes that due to gain in weight of bed.
Reaction heats calculated assuming the following reaction equations:

$$CaCO_3 + SO_2 + \frac{1}{2}O_2 = CaSO_4 + CO_2 + 77.1 \text{ kcal/mole}$$

$$MgCO_3 = MgO + CO_2 - 24.2 \text{ kcal/mole}$$

Table A.2.3.49 Distribution of carbon loss in primary cyclone fines fraction

Sample ref. 1607

Sample time 2304 to 4031 min from start of Test Series 2

Grading, microns	Wt. %	% C in stated grade	lb C/100 lb sample	% of total C in stated grade
+ 1588	Nil	-	-	-
- 1588 + 794	6.7	3.6	0.24	1.8
- 794 + 500	8.2	2.7	0.22	1.7
- 500 + 251	7.0	1.9	0.13	1.0
- 251 + 152	4.5	3.1	0.14	1.1
- 152 + 75	11.6	8.4	0.97	7.4
- 75	62.0	18.4	11.41	87.0
Total	100.0		13.11	100.0

Table A.2.3.50 Weight Losses of Corrosion Specimens $\mu g/cm^2h$

Test Series 2

Tube No.	Location of Ring	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t
1	Alloy	N		R	S	N	R	E	S	N	R	S	N	R	E		S	N	R	S	N
	Weight Loss	16	**	***	78	62	81	***	92	45	55	71	27	58	207	**	90	***	58	71	20
	Temperature (^oF)		1450													1450					
2	Alloy	W		N	W	E	N	S	R	S	N	W	S	N	W		R	E	N	R	S
	Weight Loss	18	**	21	18	208	54	70	55	45	39	***	47	***	***	**	***	212	31	41	***
	Temperature (^oF)		1290													1380					
3	Alloy	W		F_1	F_2	W	R	N	S	E	W	N	S	R	F_1		F_2	N	S	E	R
	Weight Loss	17	**	***	***	14	23	9	13	40	14	14	16	30	***	**	***	17	40	56	31
	Temperature (^oF)		1110													1170					
4	Alloy	E		F_1	F_2	W	N	R	S	W	R	N	W	S	F_1		F_2	R	S	N	R
	Weight Loss	***	**	202	277	24	***	27	30	30	31	17	32	32	305	**	361	29	37	18	29
	Temperature (^oF)		840													1110					
5	Alloy	W		F_1	F_2	R	W	N	S	R	W	S	E	N	W		R	S	N	S	W
	Weight Loss	19	**	99	99	7	17	8	8	***	***	51	15	9	18	**	10	12	7	16	16
	Temperature (^oF)		630													930					
6	Alloy	N		R	S	N	R	E	S	N	R	S	N	R	E		S	N	R	S	N
	Weight Loss	60	**	171	285	103	201	***	***	38	136	127	39	94	223	**	139	45	122	112	16
	Temperature (^oF)		1470													1470					

** Specimen used for measuring metal temperature

*** Specimen not descaled, retained for further examination.

F_1 Ferritic 1%Cr ½%Mo steel
F_2 Ferritic 2¼%Cr steel
W Ferritic 12%Cr steel

S Austenitic Type 316
R Austenitic Type 347
E Austenitic Type Esshete 1250

N Nimonic PE 16

Table A.2.3.51 Summary of weight losses of corrosion specimens

Test Series 2

Material		Tube 6		Tube 1		Tube 2		Tube 3		Tube 4		Tube 5	
		1470°F	1470°F	1450°F	1450°F	1380°F	1290°F	1170°F	1110°F	1110°F	840°F	930°F	630°F
1% Cr	Av. Loss	-	-	-	-	-	-	-	-	305	202	-	99
	Max/Min	-	-	-	-	-	-	-	-	-	-	-	-
	No. of Specimens	-	-	-	-	-	-	-	-	1	1	-	1
2¼% Cr	Av. Loss	-	-	-	-	-	-	-	-	361	277	-	151
	Max/Min	-	-	-	-	-	-	-	-	-	-	-	-
	No. of Specimens	-	-	-	-	-	-	-	-	1	1	-	1
12% Cr	Av. Loss	-	-	-	-	-	18	14	16	31	24	17	18
	Max/Min	-	-	-	-	-	18/18	-	17/14	32/30	-	18/16	19/17
	No. of Specimens	-	-	-	-	-	2	1	2	2	1	2	2
SF316	Av. Loss	127	285	78	85	46	70	28	13	35	30	14	8
	Max/Min	139/112	-	90/71	92/78	47/45	-	40/16	-	37/32	-	16/12	-
	No. of Specimens	3	1	2	2	2	1	2	1	2	1	2	1
RF36	Av. Loss	120	186	57	81	40	55	30	23	30	27	10	7
	Max/Min	135/94	201/171	58/55	-	-	-	31/29	-	31/29	-	-	-
	No. of Specimens	3	2	3	1	1	1	2	1	3	1	1	1
Esshete 1250	Av. Loss	223	-	207	-	212	208	56	40	-	-	15	-
	Max/Min	-	-	-	-	-	-	-	-	-	-	-	-
	No. of Specimens	1	-	1	-	1	1	1	1	-	-	1	-
PE16	Av. Loss	35	80	30	39	35	37	16	9	18	-	8	8
	Max/Min	45/16	103/60	45/20	62/16	39/31	54/21	17/14	-	18/17	-	9/7	-
	No. of Specimens	4	2	3	2	2	2	2	1	2	-	2	1

Notes:- (1) Under each Tube heading are given the measured metal temperatures at the outlet and inlet of each tube respectively.

(2) The "av. loss" and "max/min" are the weight losses in $\mu g/cm^2h$.

Table A.2.3.52 Metallographic examination of corrosion specimens

Test Series 2

Temp. °F	Material	Surface Texture	Deposit/ Scale	Penetration μm	
				Pits	Sulphur
1110	F1	v. rough	heavy fissured	0	0
	F2	v. rough	"	0	0
1290	W	smooth	slight	0	0
	R	smooth	slight	0	v. slight
	N	smooth	-	0	0
1470	S	rough	slight	0	40
	R	smooth	slight	0	15
	E	rough	heavy	0	25
	N	smooth	heavy	0	5

Table A.2.3.54 Analysis of Spot Samples of (Coal + Dolomite)

Test Series 3

Sample Ref	Sample time min	Moisture %	"Ash" %	CO_2 %	Size Grading: % within stated size grade						Median diameter µm
					-1588 +794 µm	-794 +500 µm	-500 +251 µm	-251 +152 µm	-152 + 75 µm	-75 + 0 µm	
1658	183	1.4	17.5	7.8	18	17	21	13	12	19	310
1659	368	1.1	23.5	12.5	27	18	19	11	9	16	410
1660	501	1.0	25.7	14.7	32	20	19	10	8	11	520
1661	683	1.1	22.0	11.4	27	17	18	12	10	16	400
1662	884	1.0	24.6	13.9	35	20	18	9	8	10	570
1663	1036	1.0	22.5	12.2	30	17	19	12	9	13	450
1664	1214	1.1	24.4	12.8	32	19	18	10	8	13	520
1665	1409	0.8	24.1	16.5	38	19	18	10	7	8	600
1666	1550	1.1	19.0	6.6	16	15	21	14	14	20	270
1667	1677	1.1	17.6	7.3	20	15	20	14	12	19	300
1668	1797	1.2	22.2	9.8	25	16	19	13	11	16	360
1669	1912	1.1	28.5	14.0	29	19	20	11	9	12	480
1670	2090	0.9	22.5	10.9	29	18	19	11	9	14	460
1671	2207	0.8	25.4	12.7	33	21	18	9	8	11	550
1672	2326	0.9	22.7	11.3	19	28	18	11	9	15	440
1673	2400	0.8	21.3	10.5	33	19	17	9	8	14	530
1674	2450	0.8	21.5	10.1	33	17	18	10	8	14	500
1675	2568	0.9	20.3	9.3	29	17	18	11	10	15	430
1676	2700	0.8	21.5	10.8	31	15	17	12	10	15	420

Analyses are given as weight percent on an "as fired" basis.

Table A.2.3.53 Operating conditions during Test Series

Test Series 3

Coal	Pittsburgh	
Coal size (upper limit)	1587	μm
Acceptor	Dolomite 1337	
Dolomite size (upper limit)	1587	μm
Coal rate	550	lb/h
Fluidising velocity	1.95	ft/s
Bed temperature	1480	°F
Combustor pressure	5	atm abs
Bed height	3.75	ft

Test No.		3.1	3.2
Elapsed time from start of test series	Start, h	25.7	36.8
	End, h	36.8	45.0
Stoichiometric ratio		1.65	1.80

Table A.2.3.55 Analysis of bulked samples of (Coal + dolomite)

Test Series 3

Test No.		3.1	3.2
Total moisture	%	1.1	0.9
Carbon dioxide	%	11.3	11.7
Volatile matter	%	49.0	49.6
Ash	%	22.0	22.2
Carbon	%	58.4	58.9
Hydrogen	%	3.5	3.6
Nitrogen	%	0.9	0.8
Sulphur	%	2.2	2.1
Oxygen + errors	%	12.9	12.3
Chlorine	%	0.07	0.07
Ash analysis			
SiO_2	%	20.0	19.5
Al_2O_3	%	8.6	9.6
Fe_2O_3	%	6.7	6.0
CaO	%	31.8	32.7
MgO	%	22.1	22.6
Na_2O	%	0.6	0.5
K_2O	%	0.7	0.6
TiO_2	%	0.4	0.4
Mn_3O_4	%	0.1	<0.1
P_2O_5	%	0.6	0.4
SO_3	%	7.1	6.9
Total	%	98.7	99.2
Ash Fusion (in Air)			
Initial deformation	°F	2515	2495
Hemisphere	°F	2515	2555
Flow	°F	2570	2570

Analyses are stated on a weight percent basis.
Total moisture and carbon dioxide are given on an 'as received' basis.
Volatile matter is given on a d.a.f. basis, and Ultimate analysis is given on a dry basis.

Table A.2.3.56 Analysis of primary cyclone fines collected by dry sampling system

Test Series 3

Test No.		3.1	3.2
Sample ref		1679	1680
Carbon	%	9.5	8.1
Hydrogen	%	0.1	0.1
Sulphur	%	3.5	4.4
Carbon dioxide	%	6.2	6.5
Chlorine	%	0.04	0.04
CaO	%	14.0	15.3
MgO	%	8.8	11.8
Na_2O	%	0.4	0.3
K_2O	%	0.8	0.7
Size Grading		% within stated size grade	
-1588 + 794 μm		1	4
- 794 + 500 μm		3	5
- 500 + 251 μm		5	7
- 251 + 152 μm		5	5
- 152 + 75 μm		10	10
- 75 + 0 μm		76	69
Median diameter μm		150	140
Mean diameter, D_p, μm		45	50

Analyses are given as weight percent, on an "as received"basis.

% Carbon does not include carbon present as Carbon dioxide.

Hydrogen assumed to be present as water.

Samples were taken approximately hourly and were then bulked.

D_p defined in Table A.2.3.8.

Table A.2.3.57 Analysis of Secondary Cyclone fines

Test Series 3

Test No.		3.1	3.2
Sample ref		1682	1683
Carbon	%	2.5	2.3
Hydrogen	%	0.1	0.1
Sulphur	%	3.0	2.8
Carbon dioxide	%	0.4	0.3
Chlorine	%	0.04	0.02
CaO	%	8.8	8.8
MgO	%	4.3	4.4
Na_2O	%	0.8	0.7
K_2O	%	1.7	1.7
Size Grading		% within stated size range	
-50 +40 μm		2	2
-40 +30 μm		4	1
-30 +20 μm		5	8
-20 +10 μm		20	16
-10 + 5 μm		45	40
- 5 + 0 μm		24	33
Median diameter, μm		7	6
Mean diameter D_p μm		5	5

Size gradings were obtained by a Coulter Count.

D_p as defined in Table A.2.3.8.

Table A.2.3.58 Analysis of exhaust dust

Test Series 3

Test No.		3.1	3.2
Sample Ref		1685	1686
Carbon	%	8.3	6.2
Hydrogen	%	0.1	0.2
Sulphur	%	3.6	3.4
Carbon dioxide	%	0.4	0.4
Chlorine	%	1.4	1.3
CaO	%	9.4	9.4
MgO	%	4.8	4.3
Na_2O	%	0.7	1.3
K_2O	%	1.4	1.6
Size grading		% within stated size range	
-60 +50 µm		1	2
-50 +40 µm		2	4
-40 +30 µm		11	4
-30 +20 µm		9	12
-20 +10 µm		15	20
-10 + 5 µm		38	33
- 5 + 0 µm		24	25
Median diameter, µm		7	8
Mean diameter, D_p µm		6	6

Analyses are given as weight percent on an 'as received' basis.
% Carbon does not include carbon present as carbon dioxide.
Size gradings were obtained by a Coulter Count.
D_p as defined in Table A.2.3.8.

Table A.2.3.59 Analysis of bulked samples of bed material

Test Series 3

Test No.		Before 3.1	3.1	3.2	After 3.2
Sample period	mins	0	1682 to 2158	2287 to 2549	2700
Sample Ref		1698	1699	1700	1701
Carbon	%	0.2	0.1	0.1	0.1
Sulphur	%	1.3	7.4	8.3	8.2
Carbon dioxide	%	0.4	11.5	10.4	9.5
Chlorine	%	0.03	0.04	0.04	0.05
CaO	%	4.4	30.4	30.4	29.6
MgO	%	2.2	22.8	21.2	20.6
Na_2O	%	1.0	0.3	0.4	0.3
K_2O	%	2.5	0.4	0.5	0.1
Sulphite sulphur		<0.01	-	<0.01	-
Sulphide sulphur		nil	-	nil	-
Size analysis		% within stated size grade			
-1588 +794 µm		12	52	53	50
- 794 +500 µm		23	28	27	29
- 500 +251 µm		45	16	17	18
- 251 +152 µm		19	3	3	2
- 152 + 0 µm		1	1	0	1
Median diameter, µm		420	830	830	800
Mean diameter, D_p, µm		350	620	640	600

Analyses are given as weight percent on an 'as received' basis.
% carbon does not include carbon present as carbon dioxide.
Sulphur not present as sulphite or sulphide is assumed to be present as sulphate.
D_p as defined in Table A.2.3.8.

Table A.2.3.60 Gas composition measurements

Test Series 3

Test No.		3.1	3.2
Elapsed time from start of Test Series	Start, h	25.7	36.8
	End, h	36.8	45.0
Operating conditions	Ca/S mol ratio	1.65	1.80
Gas composition % by volume (dry gas)	CO_2	14.6	14.1
	CO	0.02	0.07
	O_2	5.3	5.1
Gas composition p.p.m. by volume (dry gas)	SO_2	100	100
	NO_x	160 up to 22.0 hours	
	Cl	60)	
	Na_2O	1.5) at 5.1 hours	
	K_2O	0.3)	

Table A.2.3.61 Measurement of SO_2 and SO_3 in exhaust gases

Test Series 3

Time from start, min	SO_2 p.p.m. (v/v)	SO_3 p.p.m. (v/v)
238	465	0
276	308	0
312	325	0
357	212	0
397	292	0
519	157	-
600	159	-
889	145	-
968	77	-
1024	119	-
1105	178	-
1189	112	-
1239	121	-
1254	136	-
1268	113	-
1358	95	-
1569	91	-
1647	79	-
1793	76	-
1918	126	-
1985	106	-
2121	107	-
2270	154*(85)	-
2300	200*(110)	-
2345	184*(102)	-
2372	170*(94)	-
2392	174*(97)	-
2465	182*(100)	-
2480	186*(103)	-
2510	182*(100)	-
2540	187*(103)	-
2600	169*(94)	-
2630	164*(91)	-
2660	168*(94)	-

Note: At the end of Test 3 it was noticed that a blow-off valve in the analyser system was leaking. As this valve was positioned after the analysis section but before the gas meter, a leak would have the effect of making the actual sample flow rate higher than was measured, and the true SO_2 levels would be lower than indicated. Although the time at which the valve started leaking is not known it seems probable that it was after 2270 minutes when there was a sudden unexplained jump in the SO_2 values (i.e. all those values marked * in the above Table). The sampling system was recalibrated after the Test, with the leaky valve, so that a corrected flow rate could be used. The corresponding corrected SO_2 values are given in brackets.

Table A.2.3.62 Percentage Retention of Sulphur, Alkalis and Chlorine

Test Series 3

Test No.	3.1	3.2
Stoichiometric Ratio	1.65	1.80
Total Ca/S Mol Ratio	1.81	1.96
Percent Retention		
Sulphur	95.4	94.7
Sodium	97.7	97.0
Potassium	99.4	99.2
Chlorine	15.5	16.5
Percent Reduction		
Sulphur Emission	95.2	95.2

% Retention of sulphur, sodium and potassium
= 100 (Total Input-Output in Gas)/Total Input

% Retention of Chlorine
= 100 (Total Output-Output in Gas)/Total Output

% Reduction of Sulphur Emission
= 100 (Emission without acceptor - Emission observed)/(Emission without acceptor)

Emission without acceptor assumed to be 2032 p.p.m. v/v in dry gas

Stoichiometric Ratio assumed = (Total Ca/S mol ratio - 0.16)

Table A.2.3.63 Concentration of NO_x in combustion gases

Test Series 3

Time from start, min	NO_x p.p.m. (v/v)	Method
328	149	Saltzman
331	152	"
1217	168	"
1230	203	"
1240	153	Modified Saltzman
1247	194	Saltzman
1260	108	"

Table A.2.3.63A Determinations of Alkalis and Chlorine in Flue Gas

Test Series 3

Time from start	Concentration, µg/l dry gas			Concentration, p.p.m. by volume, dry gas		
h	Cl	Na_2O	K_2O	Cl	Na_2O	K_2O
5.12	90	4.2	1.3	57	1.5	0.3

Table A.2.3.64 Mass Balances for Test 3.1

Test Series 3

Flow Rates in lb/h

	Total	Ash	Carbon	Hydrogen	Nitrogen	Oxygen
Inputs						
Coal	431	46.6	306.0	20.20	5	40
Dolomite	127	66.4	16.5	0.01	-	44
Main Air	4875	-	0.6	0.81	3736	1137
Conveying Air	425	-	0.1	-	326	99
Dipleg Nitrogen	14	-	-	-	14	-
Total Input	5872	113.0	323.2	21.03	4082	1320
Outputs						
Gained by Bed	-7	-8.7	-1.0	-	-	1
Weir Solids	94	65.9	3.0	-	-	18
Primary Cyclone	56	42.4	6.3	-	-	5
Secondary Cyclone	4	3.2	0.1	-	-	0
Exhaust Dust	1	0.4	0.0	-	-	0
Flue Gas	5724	-	317.5	21.03	4062	1321
Total Output	5872	103.3	325.9	21.03	4062	1347

	Sulphur	Calcium	Magnesium	Sodium	Potassium	Chlorine
Inputs						
Coal	12.25	-0.50	-0.18	0.447	0.601	0.391
Dolomite	0.03	28.15	16.40	0.094	0.105	-
Main Air	-	-	-	-	-	-
Conveying Air	-	-	-	-	-	-
Dipleg Nitrogen	-	-	-	-	-	-
Total Input	12.28	27.65	16.22	0.541	0.707	0.391
Outputs						
Gained by Bed	1.67	0.66	-0.43	-0.017	-0.025	-0.003
Weir Solids	6.98	20.48	12.96	0.245	0.391	0.038
Primary Cyclone	1.97	5.62	2.98	0.167	0.373	0.022
Secondary Cyclone	0.11	0.23	0.09	0.021	0.051	0.001
Exhaust Dust	0.02	0.04	0.02	0.003	0.006	0.008
Flue Gas	0.56	-	-	0.013	0.004	0.365
Total Output	11.31	27.03	15.63	0.431	0.801	0.431

Dolomite analysis assumed to be as in Test Series 2.
Bed compositions interpolated from smoothed plots versus time.

Table A.2.3.65 Mass Balances for Test 3.2

Test Series 3

Flow Rates in lb/h

	Total	Ash	Carbon	Hydrogen	Nitrogen	Oxygen
Inputs						
Coal	391	41.7	282.8	18.99	4	32
Dolomite	121	63.2	15.7	0.01	-	42
Main Air	4865	-	0.6	0.81	3729	1135
Conveying Air	426	-	0.1	-	327	99
Dipleg Nitrogen	20	-	-	-	20	-
Total Input	5823	104.9	299.2	19.82	4080	1308
Outputs						
Gained by Bed	21	16.7	-0.1	-	-	3
Weir Solids	40	27.7	1.2	-	-	8
Primary Cyclone	52	38.3	5.9	-	-	6
Secondary Cyclone	2	1.8	0.1	-	-	0
Exhaust Dust	0	0.3	0.0	-	-	0
Flue Gas	5707	-	307.5	19.82	4108	1270
Total Output	5823	84.9	314.5	19.82	4108	1287
	Sulphur	**Calcium**	**Magnesium**	**Sodium**	**Potassium**	**Chlorine**
Inputs						
Coal	10.73	-0.48	-0.26	0.328	0.461	0.358
Dolomite	0.02	26.80	15.62	0.090	0.100	-
Main Air	-	-	-	-	-	-
Conveying Air	-	-	-	-	-	-
Dipleg Nitrogen	-	-	-	-	-	-
Total Input	10.75	26.32	15.35	0.418	0.561	0.358
Outputs						
Gained by Bed	2.13	3.48	1.32	-0.021	-0.601	0.029
Weir Solids	3.35	8.76	5.16	0.120	0.167	0.016
Primary Cyclone	2.31	5.73	3.73	0.117	0.304	0.021
Secondary Cyclone	0.06	0.13	0.05	0.011	0.029	0.000
Exhaust Dust	0.01	0.03	0.01	0.004	0.005	0.005
Flue Gas	0.57	-	-	0.013	0.004	0.365
Total Output	8.42	18.13	10.27	0.242	-0.091	0.437

Dolomite analysis assumed to be as in Test Series 2.
Bed compositions interpolated from smoothed plots versus time.
Flow Rate of Primary Cyclone Solids assessed by dry sampling method.

Table A.2.3.66 Heat Balances, million Btu/h

Test Series 3

Test No.	3.1	3.2
Heat Inputs		
In coal-dolomite mixture, total	5.58	5.09
In air and nitrogen, total	0.05	0.05
Heat of sulphation of $CaCO_3$	0.05	0.04
Total Heat Input	5.68	5.18
Heat Outputs		
Weir solids, total	0.03	0.02
Elutriated solids, sensible	0.01	0.02
potential	0.06	0.06
Cyclone and weir blowdowns, total	0.05	0.05
Exhaust flue gas, sensible	2.06	2.03
potential	0.00	0.02
latent	0.20	0.19
To water cooling, in bed	2.74	2.66
in freeboard	0.19	0.18
shell cooling	0.11	0.11
To shell pressurising air	0.02	0.02
Estimated radiation losses	0.01	0.01
Heat of calcination of $MgCO_3$	0.03	0.03
Total Heat Output	5.51	5.36
Unaccounted (Input-Output)	+0.17	-0.18
Unaccounted, % of Input	+3.0	-3.5

Total heats are the sums of sensible heat and of potential and/or latent heats.

Sensible heats refer to 32°F datum; the sensible heat of coal-acceptor mixture approx. 0.002 million Btu/h.

Potential heat of coal-acceptor mixture equals that of the coal fed.

Latent heat of water vapour in input gas approx. 0.02 million Btu/h.

Total heat of weir solids includes that due to gain in weight of bed.

Reaction heats calculated assuming the following reaction equations:

$CaCO_3 + SO_2 + \frac{1}{2}O_2 = CaSO_4 + CO_2 + 77.1$ kcal/mole

$MgCO_3 = MgO + CO_2 - 24.2$ kcal/mole

Table A.2.3.67 Operating conditions during Test Series

Test Series 4

Coal	Pittsburgh	
Coal size (upper limit)	1587	μm
Acceptor	Dolomite	1337
Acceptor size (upper limit)	1587	μm
Coal rate	560	lb/h
Fluidising velocity	1.95	ft/s
Bed temperature	1465	°F
Combustor pressure	4.9	atm abs
Bed height	3.75	ft.

Test No.		4.1	4.2
Elapsed time from start of test series	Start, h	21.4	68.8
	End, h	46.9	100
Stoichiometric ratio		1.54	2.02

Table A/2.3.68 Analysis of spot samples of (Coal + Dolomite)

Test Series 4

Sample Ref	Sample time min	Moisture %	"Ash" %	CO_2 %	Size Grading: % within stated size grade -1588 + 794 µm	-794 +500 µm	-500 +251 µm	-251 +152 µm	-152 + 75 µm	-75 + 0 µm	Median diameter µm
1720	125	0.7	21.0	9.6	19	13	19	14	14	23	240
1721	295	0.7	23.1	10.6	21	17	20	12	12	17	340
1722	485	0.9	21.9	10.3	19	14	19	14	13	20	280
1723	652	1.3	20.0	8.7	14	15	20	13	14	24	250
1724	853	0.6	23.5	10.5	21	15	20	13	12	19	310
1725	1011	1.0	19.9	8.5	24	18	19	10	9	20	390
1726	1197	1.0	20.0	9.2	23	16	19	12	11	19	350
1727	1387	1.2	19.8	9.2	20	16	19	12	12	21	310
1728	1555	0.8	21.1	9.6	16	15	23	15	13	17	290
1729	1735	0.8	21.6	9.6	17	16	22	13	13	18	300
1730	1914	1.2	18.6	8.2	20	16	21	14	12	17	320
1731	2095	1.2	19.6	9.0	18	16	22	13	12	19	310
1732	2270	1.1	23.0	11.1	18	15	24	15	13	16	300
1733	2503	1.1	21.5	9.5	23	19	22	11	10	15	400
1734	2700	1.2	17.9	6.4	16	14	20	14	13	22	250
1735	2875	1.1	16.9	6.6	17	16	21	13	13	20	300
1736	3079	0.9	20.9	10.3	20	17	22	14	12	16	330
1737	3274	0.8	22.9	11.1	19	18	23	13	11	16	350
1738	3481	0.7	21.1	10.2	17	16	23	15	13	17	300
1739	3616	0.9	21.5	9.6	21	19	22	12	11	15	380
1740	3832	0.8	21.7	10.8	18	17	22	15	12	16	320
1741	3970	0.8	24.2	12.2	19	18	23	14	12	15	340
1742	4164	0.9	23.3	12.4	16	15	23	16	14	16	280
1743	4344	1.0	19.7	9.3	20	20	22	10	9	19	380
1744	4525	0.9	22.2	11.0	27	19	20	11	8	17	420
1745	4732	1.1	18.9	8.8	15	16	21	13	13	22	280
1746	4877	1.0	20.3	10.4	23	17	20	12	11	18	360
1747	5058	1.0	20.7	10.0	19	17	21	11	11	23	310
1748	5239	0.9	22.3	10.6	20	17	21	13	11	18	330
1749	5421	0.9	24.3	13.5	24	20	20	10	8	18	420
1750	5610	0.8	21.8	11.1	13	13	20	16	15	23	220
1751	5786	0.9	23.9	12.4	14	13	21	15	16	21	240
1752	5960	1.0	23.5	11.8	9	10	17	17	21	27	170

Analyses are given as weight % on an "as received" basis

Table A.2.3.69 Analysis of Bulked Samples of (coal + dolomite)

Test Series 4

Test		4.1	4.2
Sample Ref		1753	1754
Proximate analysis			
Moisture	%	1.3	1.2
Volatile matter	%	46.5	49.2
'Ash'	%	20.7	22.0
Carbon dioxide	%	9.5	11.3
Ultimate analysis			
'Ash'	%	20.7	22.0
Carbon	%	60.8	57.9
Hydrogen	%	3.9	3.6
Nitrogen	%	1.1	1.1
Sulphur	%	2.2	2.0
Oxygen + errors	%	10.6	13.0
Chlorine	%	0.08	0.07
Ash analysis			
SiO_2	%	20.2	17.3
Al_2O_3	%	8.5	7.3
Fe_2O_3	%	7.1	5.7
CaO	%	31.6	34.7
MgO	%	21.1	23.7
Na_2O	%	0.9	0.9
K_2O	%	0.5	0.4
Mn_3O_4	%	0.1	0.1
P_2O_5	%	0.4	0.5
TiO_2	%	0.5	0.4
SO_3	%	6.7	7.4
Ash fusion (in air)			
Initial deformation	°F	2498	2498
Hemisphere	°F	2516	2516
Fusion	°F	2534	2534

Analyses are given on a weight percent basis.
Total moisture and carbon dioxide are given on an 'as received' basis.
Volatile matter is given on a d.a.f. basis, and
Ultimate analysis is given on a dry basis.

Table A.2.3.70 Analysis of Raw Coal

Test Series 4

Sample Ref		1579	1643	1648
Proximate				
Moisture	%	1.5		1.5
Volatile matter	%	42.3		41.3
'Ash'	%	13.8		12.8
Fixed Carbon	%	49.7		50.3
Carbon dioxide	%	0.6		0.5
Ultimate				
'Ash'	%	13.8		12.8
Carbon	%			73.3
Hydrogen	%			4.9
Nitrogen	%			1.0
Sulphur	%	2.9		3.0
Oxygen + errors	%			4.8
Calorific value	Btu/lb			15088
Ash Analysis				
CaO	%		6.5	
MgO	%		1.5	
Na_2O	%		0.7	
K_2O	%		1.6	
Ash Fusion (H_2/CO_2)				
Initial deformation	°F	2050		
Hemisphere	°F	2140		
Flow	°F	2370		

Analyses are given on a weight percent basis.
Volatile matter and calorific value are given on a d.a.f. basis.
Moisture, 'ash', fixed carbon and CO_2 are given on air dry basis.
Remainder of ultimate analysis are given on dry basis.

Table A.2.3.71 Analysis of Shale and dolomite

Test Series 4

Material		Shale	Dolomite
Sample Ref		1769	1719
Moisture	%	-	<0.05
Loss on ignition at 800°C	%	-	46.4
SiO_2	%	54.3	1.1
Al_2O_3	%	22.9	Nil
Fe_2O_3	%	4.6	0.1
CaO	%	1.8	31.0
MgO	%	1.1	20.8
Na_2O	%	0.6	0.4
K_2O	%	3.3	0.6
S	%	0.6	<0.05
CO_2	%	-	47.7
Size grading		% within stated size range	
-1588 +794 μm		23	28
- 794 +500 μm		24	18
- 500 +251 μm		25	13
- 251 +152 μm		9	9
- 152 + 75 μm		5	13
- 75 + 0 μm		14	20
Median size, μm			400
Mean diameter, D_p, μm			125

Analyses are on weight percent basis

D_p as defined in Table A.2.3.8.

Table A.2.3.72 Chemical Analysis of Primary Cyclone Fines: collected by dry sampling system

Test Series 4

Test		4.1	4.2
Sample ref		1755	1756
Carbon	%	4.3	3.6
Hydrogen	%	0.05	0.1
Sulphur	%	5.4	4.1
Carbon dioxide	%	8.8	12.5
Chlorine	%	0.04	0.05
CaO	%	22.0	25.7
MgO	%	14.6	18.2
Na_2O	%	0.9	0.3
K_2O	%	0.9	0.4
-1588 + 794 μm		9	12
- 794 + 500 μm		10	13
- 500 + 251 μm		14	16
- 251 + 152 μm		7	11
- 152 + 75 μm		11	23
- 75 + 0 μm		49	25
Median diameter μm		80	170
Mean diameter, D_p, μm		65	95

Analyses are given as weight percent, on an 'as received' basis.

Carbon does not include carbon present as carbon dioxide.

D_p as defined in Table A.2.3.8.

Table A.2.3.73 Analysis of Secondary Cyclone Fines collected by dry sampling system

Test Series 4

Test		4.1	4.2
Sample Ref		1759	1760
Carbon	%	4.3	4.3
Hydrogen	%	0.1	0.1
Sulphur	%	4.0	4.1
Carbon dioxide	%	0.8	1.3
Chlorine	%	0.02	0.05
CaO	%	10.4	12.2
MgO	%	6.1	6.8
Na_2O	%	0.7	0.7
K_2O	%	1.3	1.2
Size grading		% within stated size range	
-75 +60	μm	0	0
-60 +50	μm	0	0
-50 +40	μm	1	0
-40 +30	μm	5	5
-30 +20	μm	13	11
-20 +10	μm	30	31
-10 + 5	μm	27	31
- 5 + 0	μm	25	23
Median diameter, μm		10	9
Mean diameter, D_p, μm		8	8

Analyses are given as weight percent, on an 'as received' basis.
% carbon does not include carbon present as carbon dioxide.
Size gradings refer to Coulter count of the material passing a 75 μm sieve.
D_p as defined in Table A.2.3.8.

Table A.2.3.74 Analysis of Exhaust Dust
Test Series 4

Test		4.1	4.2
Sample Ref		1763	1764
Carbon	%	2.9	2.9
Sulphur	%	5.9	6.3
Carbon dioxide	%	0.6	0.5
Chlorine	%	1.40	1.08
CaO	%	12.2	5.3
MgO	%	15.0	6.5
Na_2O	%	0.6	1.4
K_2O	%	1.1	1.3
Size grading		% within stated size range	
-75 +60 µm		5	4
-60 +50 µm		1	2
-50 +40 µm		2	1
-40 +30 µm		7	2
-30 +20 µm		14	28
-20 +10 µm		31	19
-10 + 5 µm		32	34
- 5 + 0 µm		6	9
Median diameter µm		14	13
Mean diameter, D_p, µm		9	8

Analyses are given as weight percent on an 'as received' basis.

Carbon does not include carbon present as carbon dioxide.

Size gradings refer to Coulter count of the material passing a 75 µm sieve.

D_p as defined in Table A.2.3.8.

Table A.2.3.75 Analysis of bed material

Test Series 4

Test No.		Before 4.1	Start of 4.1	4.1	End of 4.1	Start of 4.2	4.2	After 4.2
Sample Ref		1773	1774	1775	1776	1777	1778	1779
Sample time mins		0	965 to 1510	1510 to 2800	2800	4125	4125 to 5882	6000
Chemical analysis								
Carbon	%	0.1	0.1	<0.1	0.1	0.1	0.1	0.1
Sulphur	%	1.0	6.4	8.0	9.4	9.0	8.7	8.8
Carbon dioxide	%	0.4	5.6	6.6	7.2	9.9	10.1	10.5
Chlorine	%	0.01	0.02	0.02	0.03	0.04	0.04	0.05
CaO	%	2.8	20.6	24.0	28.0	31.1	31.0	32.0
MgO	%	1.9	13.8	16.1	18.0	18.9	20.6	20.4
Na_2O	%	0.8	0.5	0.5	0.4	0.6	0.4	0.4
K_2O	%	2.3	1.0	0.8	0.4	0.4	0.6	0.4
Size grading		% within stated size range						
−1588 + 794	μm	16	37	44	55	54	53	51
− 794 + 500	μm	26	24	24	25	24	27	30
− 500 + 251	μm	42	28	23	17	15	17	15
− 251 + 152	μm	13	10	7	2	5	3	1
− 152 + 75	μm	2	1	1	0	2	0	1
− 75 + 0	μm	1	1	1	0	2	0	3
Median diameter, μm		458	625	720	858	846	828	811
Mean diameter, D_p, μm		360	450	500	660	490	640	430

Analyses are given as weight percent, on an "as received" basis.

% Carbon does not include carbon present as carbon dioxide.

D_p as defined in Table A.2.3.8.

Table A.2.3.76 Gas composition measurements

Test Series 4

Test No.		4.1	4.2
Elapsed time from start of Test Series	Start, h	21.4	68.8
	End, h	46.9	100
Operating conditions	Ca/S mol ratio	1.54	2.02
Gas composition % by volume (dry gas)	CO_2 CO O_2	14.4 .02 5.8	14.7 .02 5.3
Gas composition p.p.m. by volume (dry gas)	SO_2 NO_x Cl Na_2O K_2O	130 140 40 1.5 0.4	50 190 40 1.5 0.5

Table A.2.3.77 Variation in gas composition

Test Series 4

Oxygen in combustion products

Test No.	% of test time in stated range					Mean Oxygen %
	<1%	1 - 2%	2 - 4%	4 - 6%	>6%	
4.1	<1	2	7	52	38	5.8
4.2	0	2	12	62	14	5.3

Carbon monoxide in combustion products

Test No.	% of test time in stated range			Mean CO %
	0 to 0.01%	0.01 to 0.02%	>0.02%	
4.1	36	60	4	.02
4.2	14	60	26	.02

Table A.2.3.78 Variation of temperature in bed and freeboard

Test Series 4

Height above distributor	Test No.	% of test time in stated temperature ranges					Mean temp. °F
		<1400°F	1400° to 1436°F	1436°F to 1472°F	1472° to 1508°F	>1508°F	
Bed 1¼ in to 5 in	4.1	1	18	53	25	3	1455
	4.2	0	10	59	29	2	1470
Bed 13 in to 16 in	4.1	1	10	47	36	6	1465
	4.2	0	7	39	50	4	1475
Bed 36 in	4.1	0	0	23	59	18	1475
	4.2	0	0	7	64	29	1500
Freeboard 77 in	4.1	–	–	–	–	–	1415
	4.2	29	29	36	7	0	1425
Freeboard 107 in	4.1	9	30	43	18	0	1440
	4.2	22	34	41	3	0	1420

Table A.2.3.79 Measurements of SO_2 in Exhaust Gases

Test Series 4

Time from start Min	SO_2 p.p.m. (v/v)	Time from start Min	SO_2 p.p.m. (v/v)
129	187	3020	165
206	190	3104	129
292	154	3213	86
375	107	3297	99
421	143	3419	81
543	70	3486	67
565	114	3547	63
663	113	3641	72
814	157	3731	80
868	188	3787	80
1003	138	3863	71
1057	155	4084	49
1115	169	4171	58
1246	116	4330	32
1346	129	4468	54
1626	111	4571	43
1743	145	4702	31
1861	105	4819	69
1910	102	4917	62
2060	127	5055	52
2235	132	5242	64
2386	122	5278	59
2502	119	5527	39
2571	147	5627	25
2801	146	5765	44
2911	188	5861	34
		5954	65

Note: No measurements of SO_3 were made in this test.

Table A.2.3.80 Percentage Retention of Sulphur, Alkalis and Chlorine

Test Series 4

Test No.	4.1	4.2
Stoichiometric ratio	1.54	2.02
Total Ca/S mol ratio	1.70	2.18
Percent Retention		
Sulphur	94.1	97.5
Sodium	98.3	98.5
Potassium	98.8	98.3
Chlorine	15.4	22.8
Percent Reduction		
Sulphur Emission	93.8	97.6

% Retention of sulphur, sodium and potassium
= 100 (Total input-output in gas)/Total input

% Retention of Chlorine
= 100 (Total Output-Output in Gas)/Total output

% Reduction of Sulphur Emission
= 100 (Emission without acceptor - emission observed)/(Emission without acceptor)

Emission without acceptor assumed to be 2032 p.p.m. v/v in dry gas

Stoichiometric ratio assumed = (Total Ca/S mole ratio - 0.16)

Table A.2.3.81 Comparison of measurements of SO_2 by infra-red and chemical method

Test Series 4

Sample No.	Chemical method SO_2 p.p.m.	Av. from I.R. SO_2 p.p.m.	Max/min from I.R. SO_2 p.p.m.
57	65	60	35/80
56	34	70	55/85
55	44	70	55/90 (I.R. suspect)
53	39	35	25/55
52	59	60	20/115
51	64	65	35/110
50	52	50	30/95
49	62	50	30/75
48	69	50	30/105
47	31	25	15/30
46	43	40	30/65
45	54	45	30/85
44	32	30	25/45
43	54	45	35/80
42	49	45	25/75
40	80	70	35/140
37	63	30	20/50
34	99	100	50/175
33	86	75	40/100
32	129	135	90/170
31	165	160	55/230
28	147	120	80/165

Notes: (i) Chemical method was based on approx. 10 minute sample periods

(ii) The infra red sample was sampled continuously from a Tee in the sample line. The figures quoted above are taken from the recorder chart over the same period as the "chemical" samples.

Table A.2.[illegible] Determinations of Alkalis and Chlorine in Flue Gas

Test Series 4

Time from start, h	Concentration, µg/l dry gas			Concentration, p.p.m. by volume, dry gas		
	Cl	Na_2O	K_2O	Cl	Na_2O	K_2O
42.22	67	4.3	1.6	43	1.5	0.4
86.63	69	4.3	2.2	44	1.5	0.5

A.2.3.82 Concentration of NO_x in combustion gases

Test Series 4

Time from start min	NO_x concentration p.p.m. (v/v)	Method
655-668	128	Modified Saltzman
689-706	129	Saltzman
707-724	127	"
724-751	117	"
848-878	117	"
2095-2105	136	"
2105-2110	130	Modified Saltzman
2290-2296	132	Hersch
2297-2306	156	Saltzman
2357-2369	155	Hersch
2413-2415	149	"
3455-3465	195	Saltzman
3465-3475	194	"
3477-3490	190	"
3494-3513	194	Hersch
3520-3536	200	"
4939-4947	187	Saltzman
4950-4959	185	"
4964-4970	226	Modified Saltzman
4974-4986	174	Saltzman

Table A.2.3.84 Mass Balances for Test 4.1

Test Series 4

Flow Rates in lb/h

	Total	Ash	Carbon	Hydrogen	Nitrogen	Oxygen
Inputs						
Coal	447	51.0	318.7	21.74	6	37
Dolomite	104	54.4	13.6	0.00	-	36
Main Air	4871	-	0.6	0.98	3732	1137
Conveying Air	362	-	0.0	-	278	84
Dipleg Nitrogen	19	-	-	-	19	-
Total Input	5803	105.4	332.9	22.72	4035	1294
Outputs						
Gained by Bed	-	-6.1	0.4	-	-	4
Weir Solids	23	17.0	0.4	-	-	4
Primary Cyclone	64	47.0	4.3	-	-	9
Secondary Cyclone	2	1.6	0.1	-	-	0
Exhaust Dust	1	0.6	0.0	-	-	0
Flue Gas	5713	-	310.7	22.72	4038	1340
Total Output	5803	60.0	315.9	22.72	4038	1358

	Sulphur	Calcium	Magnesium	Sodium	Potassium	Chlorine
Inputs						
Coal	12.10	2.43	1.31	0.445	-0.050	0.441
Dolomite	0.02	23.08	13.07	0.309	0.519	-
Main Air	-	-	-	-	-	-
Conveying Air	-	-	-	-	-	-
Dipleg Nitrogen	-	-	-	-	-	-
Total Input	12.12	25.51	14.38	0.754	0.469	0.441
Outputs						
Gained by Bed	1.99	3.35	1.63	-0.053	-0.324	0.007
Weir Solids	1.85	3.97	2.25	0.086	0.154	0.005
Primary Cyclone	3.48	10.14	5.68	0.431	0.482	0.026
Secondary Cyclone	0.07	0.14	0.07	0.010	0.020	0.000
Exhaust Dust	0.04	0.06	0.07	0.003	0.007	0.010
Flue Gas	0.72	-	-	0.013	0.005	0.271
Total Output	8.16	17.66	9.69	0.489	0.344	0.319

Test was in two parts separated by 1.67 hours of operation at a reduced rating. Bed compositions interpolated from smoothed plots versus time. Hydrogen contents of primary and secondary cyclone solids assumed to be due to moisture absorbed after weighing, and the analyses have been corrected to the dry basis.

Table A.2.3.85 Mass Balances for Test 4.2

Test Series 4

Flow Rates in lb/h

	Total	Ash	Carbon	Hydrogen	Nitrogen	Oxygen
Inputs						
Coal	441	48.5	309.7	21.32	6	44
Dolomite	130	67.8	16.9	0.00	-	45
Main Air	4874	-	0.6	0.92	3735	1137
Conveying Air	382	-	0.0	-	293	89
Dipleg Nitrogen	18	-	-	-	18	-
Total Input	5845	116.3	327.3	22.24	4053	1314
Outputs						
Gained by Bed	-2	-1.1	0.1	-	-	-0
Weir Solids	41	27.7	1.2	-	-	8
Primary Cyclone	103	75.2	7.4	-	-	16
Secondary Cyclone	2	1.9	0.1	-	-	0
Exhaust Dust	1	0.7	0.0	-	-	0
Flue Gas	5700	-	316.1	22.24	4037	1323
Total Output	5845	104.3	324.9	22.24	4037	1347
	Sulphur	Calcium	Magnesium	Sodium	Potassium	Chlorine
Inputs						
Coal	11.39	2.38	1.66	0.453	-0.230	0.400
Dolomite	0.03	28.78	16.29	0.385	0.647	-
Main Air	-	-	-	-	-	-
Conveying Air	-	-	-	-	-	-
Dipleg Nitrogen	-	-	-	-	-	-
Total Input	11.42	31.15	17.96	0.839	0.417	0.400
Outputs						
Gained by Bed	-0.32	-0.03	0.29	-0.088	-0.006	0.005
Weir Solids	3.55	9.03	5.06	0.121	0.203	0.016
Primary Cyclone	4.24	19.02	11.36	0.230	0.344	0.052
Secondary Cyclone	0.09	0.19	0.09	0.012	0.022	0.001
Exhaust Dust	0.05	0.03	0.03	0.009	0.009	0.009
Flue Gas	0.28	-	-	0.013	0.007	0.277
Total Output	7.90	28.24	16.85	0.297	0.579	0.360

Bed compositions interpolated from smoothed plots versus time.
Hydrogen contents of primary and secondary cyclone solids assumed to be due to moisture absorbed after weighing, and thr analyses have been corrected to the dry basis.

Table A.2.3.86 Heat Balances, million Btu/h

Test Series 4

Test No.	4.1	4.2
Heat Inputs		
In coal-dolomite mixture, total	5.74	5.68
In air and nitrogen, total	0.05	0.05
Heat of sulphation of $CaCO_3$	0.05	0.05
Total Heat Input	5.84	5.78
Heat Outputs		
Weir solids, total	0.01	0.01
Elutriated solids, sensible	0.02	0.04
potential	0.04	0.06
Cyclone and weir blowdowns, total	0.05	0.05
Exhaust flue gas, sensible	2.04	2.02
potential	0.00	0.00
latent	0.21	0.21
To water cooling, in bed	2.79	2.84
in freeboard	0.21	0.24
shell cooling	0.07	0.08
To shell pressurising air	0.02	0.03
Estimated radiation losses	0.01	0.01
Heat of calcination of $MgCO_3$	0.02	0.03
Total Heat Output	5.49	5.62
Unaccounted (Input-Output)	+0.35	+0.16
Unaccounted, % of Input	+6.0	+2.8

Total heats are the sums of sensible heat and of potential and/or latent heats.
Sensible heats refer to 32°F datum; the sensible heat of coal-acceptor mixture approx. 0.002 million Btu/h.

Potential heat of coal-acceptor mixture equals that of the coal fed.

Latent heat of water vapour in input gas approx. 0.02 million Btu/h.

Total heat of weir solids includes that due to gain in weight of bed.

Reaction heats calculated assuming the following reaction equations:

$CaCO_3 + SO_2 + \frac{1}{2}O_2 = CaSO_4 + CO_2 + 77.1$ kcal/mole

$MgCO_3 = MgO + CO_2 - 24.2$ kcal/mole

Table A.2.3.87 Weight Losses of Corrosion Specimens - $\mu g/cm^2h$

Test Series 4

Tube No.	Location of Ring	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t
1	Alloy	N		R	S	N	R	E	R	N	R	S	N	R	E		S	N	R	E	N
	Weight Loss	36	**	***	7	47	25	47	14	11	13	17	40	23	144	**	18	***	14	85	38
	Temperature (^oF)		1450													1450					
2	Alloy	W		N	W	E	N	S	R	E	N	W	S	N	R		W	E	N	R	S
	Weight Loss	12	**	12	10	99	***	37	16	86	32	15	45	26	30	**	9	72	22	18	***
	Temperature (^oF)		1290													1400					
3	Alloy	W		F_1	F_2	W	R	N	S	E	W	N	E	R	F_1		F_2	N	S	E	R
	Weight Loss	8	**	256	289	10	9	11	24	***	10	15	32	8	***	**	***	7	42	50	11
	Temperature (^oF)		1040													1180					
4	Alloy	E		F_1	F_2	W	N	R	S	W	R	N	W	E	F_1		F_2	R	S	N	R
	Weight Loss	***	**	1066	***	10	***	12	14	8	21	11	10	30	1518	**	***	24	21	13	14
	Temperature (^oF)		970													1000					
5	Alloy	W		F_1	F_2	R	W	N	S	R	W	R	E	N	R		W	E	N	S	W
	Weight Loss	5	**	24	31	6	3	3	3	***	***	5	8	3	5	**	5	7	3	7	7
	Temperature (^oF)		750													1020					
6	Alloy	N		R	S	N	R	E	S	N	R	S	N	R	S		E	N	R	S	N
	Weight Loss	35	**	26	72	9	47	***	***	26	18	65	11	45	82	**	114	13	25	87	39
	Temperature (^oF)		1490													1490					

** Specimen used for measuring metal temperature

*** Specimen not descaled, retained for further examination.

F_1	Ferritic 1%Cr ½%Mo steel	S	Austenitic Type 316
F_2	Ferritic 2¼%Cr steel	R	Austenitic Type 347
W	Ferritic 12%Cr steel	E	Austenitic Type Esshete 1250

N Nimonic PE 16

Table A.2.3.88 Summary of weight losses of corrosion specimens

Test Series 4

Material		Tube 6		Tube 1		Tube 2		Tube 3		Tube 4		Tube 5	
		1490°F	1490°F	1450°F	1450°F	1400°F	1290°F	1180°F	1040°F	1000°F	970°F	1020°F	750°F
1% Cr	Av. loss	-	-	-	-	-	-	-	-	1513	1066	-	24
	Max/Min	-	-	-	-	-	-	-	-	-	-	-	-
	No. of Specimens	-	-	-	-	-	-	-	-	1	1	-	1
2¼% Cr	Av. loss	-	-	-	-	-	-	-	-	-	-	-	31
	Max/Min	-	-	-	-	-	-	-	-	-	-	-	-
	No. of Specimens	-	-	-	-	-	-	-	-	-	-	-	1
12% Cr	Av. loss	-	-	-	-	12	11	10	9	9	10	7	4
	Max/Min	-	-	-	-	15/9	412/10	-	10/8	10/8	-	8/5	5/3
	No. of Specimens	-	-	-	-	2	2	1	2	2	1	3	2
SF316	Av. loss	78	72	18	7	45	37	42	24	21	14	7	3
	Max/Min	87/65	-	18/17	-	-	-	-	-	-	-	-	-
	No. of Specimens	3	1	2	1	1	1	1	1	1	1	1	1
RF36	Av. loss	30	35	17	20	24	16	10	9	17	12	5	6
	Max/Min	45/18	47/26	23/13	25/14	30/18	-	11/8	-	21/14	-	5/5	-
	No. of Specimens	3	2	3	2	2	1	2	1	3	1	2	1
Esshete 1250	Av. loss	114	-	110	47	79	99	41	-	-	-	7	-
	Max/Min	-	-	144/85	-	86/79	-	50/32	-	-	-	-	-
	No. of Specimens	1	-	2	1	2	1	2	-	-	-	1	-
PE 16	Av. loss	22	22	39	41	27	12	11	11	12	-	3	3
	Max/Min	39/11	35/9	40/38	47/36	32/22	-	15/7	-	13/11	-	3/3	-
	No. of Specimens	4	2	2	2	3	1	2	1	2	-	2	1

Notes:- (1) Under each Tube heading are given the measured metal temperatures at the outlet and inlet of each tube respectively.

(2) The "av. loss" and "max/min" are the weight losses in $\mu g/cm^2h$.

Table A.2.3.89 Metallographic examination of corrosion specimens

Test Series 4

Temp. °C	Material	Surface Texture	Deposit/ Scale	Penetration µm	
				Pits	Sulphur
800	F1	rough	-	0	0
	F2	rough	-	0	0
	W	smooth	-	0	0
	S	smooth	-	0	0
	R	smooth	-	0	0
	E	smooth	-	0	0
	N	smooth	-	0	0
1000	F1	very rough	heavy scale	0	0
	F2	very rough	heavy scale	0	0
	W	smooth	-	0	0
	S	smooth	-	0	5
	R	smooth	-	0	9
	E	smooth	-	0	5
	N	smooth	-	0	0
1110	F1	very rough	loose grain	0	0
	F2	very rough	loose grain	0	0
	W	smooth	-	0	0
	S	smooth	-	0	5
	R	smooth	-	0	0
	E	smooth	-	0	5
	N	smooth	-	0	0
1290	W	smooth	-	0	0
	S	smooth	-	0	8
	R	smooth	-	0	14
	E	rough	scale	0	10
	N	smooth	-	0	1
1470	S	smooth	-	0	30
	R	smooth	-	0	15
	E	rough	-	0	15
	N	smooth	-	0	5

Test Series 5

Coal	Pittsburgh	
Coal size (upper limit)	1587	µm
Acceptor size (upper limit)	1587	µm
Coal rate	550	lb/h
Fluidising velocity	2.0	ft/s
Bed temperature	1465	°F
Combustor pressure	4.9	atm abs
Bed height	3.75	ft

Test No.		5.1	5.2	5.3
Elapsed time from start of test series	Start, h	16.2	48.1	78
	End, h	39.2	64.1	86.2
Acceptor		Limestone 18	Limestone 18	Dolomite 1337
Stoichiometric ratio		1.87	2.38	1.08

Table A.2.3.91 Analysis of spot sample (coal + acceptor)

Test Series 5

Sample Ref	Sample time min	Moisture %	"Ash" %	CO_2 %	Size grading: % in stated size grade						Median diameter µm
					+794 -1588 µm	+500 -794 µm	+251 -500 µm	+152 -251 µm	+ 75 -152 µm	-75 µm	
1780/1-2	113-236	1.1	22.8	6.4	10	12	14	27	16	22	220
1780/3-4	360-477	1.1	20.6	5.7	11	14	15	23	14	25	240
1780/5-6	594-716	0.8	22.4	6.2	12	14	15	28	15	17	260
1780/7-8	834-961	1.0	23.1	21.4	13	16	17	25	13	15	300
1780/9-10	1073-1190	0.9	6.8	5.8	11	14	14	28	16	17	250
1781/11-12	1310-1434	1.1	21.1	5.9	12	15	15	28	15	16	130
1781/13-14	1554-1677	1.0	19.8	5.3	15	16	15	24	14	16	290
1781/15-16	1794-1914	1.3	20.0	5.3	14	15	14	26	15	17	260
1781/17-18	2035-2152	1.2	21.7	5.9	11	16	17	26	14	16	280
1781/19-20	2269-2392	1.2	22.5	6.5	13	14	15	28	14	16	270
1781/21-22	2512-2633	1.5	22.7	7.4	17	17	18	22	11	15	330
1782/23-24	2750-2875	0.9	26.3	8.3	13	15	17	27	14	14	280
1782/25-26	3054-3173	1.0	25.3	8.3	13	14	15	26	14	16	270
1782/27-28	3282-3396	0.7	21.6	7.3	16	17	17	24	12	15	320
1782/29-30	3473-3593	0.9	24.3	7.5	13	14	14	29	14	16	130
1782/31-32	3660-3834	0.9	23.4	7.1	15	16	16	23	13	18	280
1782/33-34	3955-4074	0.9	20.6	7.5	16	17	16	28	12	12	320
1782/35-36	4194-4314	1.1	20.0	7.6	18	19	17	25	11	10	360
1782/37-38	4433-4554	1.1	22.2	8.2	19	20	19	23	11	9	380
1782/39-40	4673-4793	1.0	21.1	8.4	19	18	23	14	11	16	340
1782/41-42	4913-5031	1.0	18.2	6.4	17	19	22	12	11	19	340
1782/45	5395	1.1	14.7	4.4	21	17	21	14	11	16	350
1782/46	5515	1.1	15.1	4.7	23	19	26	6	14	13	390
1782/47	5636	1.0	14.6	4.2	18	16	22	14	12	19	300
1782/48	5776	1.0	15.4	4.9	17	17	23	13	17	13	320
1782/49	5882	1.0	14.8	4.4	14	16	23	16	14	19	270
1782/50	6000	1.0	16.8	5.7	18	18	23	13	16	12	330

Analyses are given in weight percent on an "as received" basis.

Test Series 5

Test No.		5.1	5.2	5.3
Sample ref.		1783	1784	1785
Proximate analysis				
Moisture	%	1.0	1.1	1.1
Volatile matter	%	45.0	53.6	49.5
'Ash'	%	21.9	24.6	20.1
Carbon dioxide	%	5.9	7.6	7.7
Ash	%	21.9	24.6	20.1
Carbon	%	63.0	59.4	63.1
Hydrogen	%	4.0	3.7	4.0
Nitrogen	%	1.3	1.2	1.0
Sulphur	%	2.2	2.2	2.3
Oxygen + errors	%	7.2	8.6	9.1
Chlorine	%	0.07	0.07	0.08
Ash analysis				
SiO_2	%	31.6	32.1	34.2
Al_2O_3	%	12.4	10.3	10.9
Fe_2O_3	%	8.6	7.0	7.7
CaO	%	35.7	39.7	24.8
MgO	%	1.6	1.8	15.6
Na_2O	%	1.0	0.9	0.8
K_2O	%	0.8	0.9	0.8
TiO_2	%	0.6	0.5	0.5
Mn_3O_4	%	0.1	0.1	0.1
P_2O_5	%	0.4	0.4	0.4
SO_3	%	7.2	6.3	14.3
Ash fusion (in air)				
Initial deformation	°F	2170	2230	2410
Hemisphere	°F	2230	2260	2430
Flow	°F	2280	2300	2480

Analyses are given on a weight per cent basis.
Total moisture and carbon dioxide are given on an 'as received' basis.
Volatile matter is given on a d.a.f. basis, and -
Ultimate analysis is given on a dry basis.

Table A.2.3.93 Analysis of Shale, Limestone and Dolomite

Test Series 5

Material Sample Ref		Shale* 1807	Limestone 1828	Dolomite 1719
Total moisture	%	-	0.1	< 0.05
SiO_2	%	52.6	11.9	1.1
Al_2O_3	%	23.7	0.4	Nil
Fe_2O_3	%	5.0	0.5	0.1
CaO	%	0.9	46.0	31.0
MgO	%	1.5	0.9	20.8
Na_2O	%	0.7	0.4	0.4
K_2O	%	2.3	0.1	0.6
Sulphur	%	-	0	< 0.05
Carbon	%	0.7	-	-
Carbon dioxide	%	-	36.8	47.7
Total	%	87.4	97.1	
Loss on ignition in air at 800°C	%	-	35.0	46.4
Size grading		% within stated size range		
-1588 +794 µm		31	16	28
- 794 +500 µm		30	15	17
- 500 +251 µm		25	21	14
- 251 +152 µm		8	18	8
- 152 + 75 µm		2	10	13
- 75 + 0 µm		4	20	20
Median diameter, µm		610	270	400
Mean diameter, D_p, µm		330	120	130

Analyses are given as weight per cent on an 'as received' basis.

D_p as defined in Table A.2.3.8

* Used for start-up.

Table A.2.3.94 Analysis of primary cyclone fines: collected by dry sampling system

Test Series 5

Test No. Sample ref.		5.1 1786	5.2 1787	5.3 1788
Carbon	%	3.8	1.5	3.1
Hydrogen	%	0.1	0.1	0.1
Sulphur	%	4.3	4.9	5.8
Carbon dioxide	%	8.2	11.5	8.4
Chlorine	%	0.02	0.02	0.02
CaO	%	23.8	28.5	22.8
MgO	%	0.9	1.3	9.0
Na_2O	%	0.6	0.6	0.5
K_2O	%	1.0	0.7	0.7
Size grading		% within stated size range		
-1588 +794 μm		6	4	5
-794 +500 μm		9	7	8
-500 +251 μm		14	13	13
-251 +152 μm		14	12	11
-152 + 75 μm		12	21	9
- 75 + 0 μm		45	43	54
Median diameter μm		100	90	50
Mean diameter, D_p, μm		70	70	60

Analyses are given as weight per cent on an 'as received' basis.

% carbon does not include carbon present as carbon dioxide.

D_p as defined in Table A.2.3.8.

Table A.2.3.95 Analysis of secondary cyclone fines

Test Series 5

Test No. Sample ref		5.1 1793	5.2 1794	5.3 1795
Carbon	%	2.2	1.3	2.1
Hydrogen	%	0.1	0.1	0.05
Sulphur	%	4.6	5.3	3.5
Carbon dioxide	%	0.6	1.0	0.4
Chlorine	%	0.02	0.02	0.02
CaO	%	11.1	13.5	8.6
MgO	%	1.2	1.3	4.1
Na_2O	%	0.7	1.0	0.9
K_2O	%	1.6	1.6	1.6
Size grading		% within stated size range		
-40 +30 μm		3	3	2
-30 +20 μm		5	2	5
-20 +10 μm		17	14	16
-10 + 5 μm		60	64	62
- 5 + 0 μm		15	17	15
Median diameter, μm		7	6	7
Mean diameter, D_p, μm		6	5	6

Analyses are given as weight per cent, on an 'as received' basis.

% carbon does not include carbon present as carbon dioxide.

D_p as defined in Table A.2.3.8.

Table A.2.3.96 Analysis of exhaust dust

Test Series 5

Test No. Sample ref		5.1 1800	5.2 1801	5.3 1802 *
Carbon	%	2.8	2.3	-
Hydrogen	%	0.2	0.4	-
Sulphur	%	6.1	7.6	-
Carbon dioxide	%	0.3	0.2	-
Chlorine	%	0.19	0.27	-
Size grading		% within stated size range		
-50 +40 μm		1	3	0
-40 +30 μm		0	6	2
-30 +20 μm		11	15	11
-20 +10 μm		16	22	12
-10 + 5 μm		47	40	54
- 5 + 0 μm		15	14	21
Median diameter, μm		8	9	6
Mean diameter, D_p, μm		6	7	5

Analyses are given as weight per cent, on an 'as received' basis.

Insufficient sample available for determination of CaO, MgO, Na_2O and K_2O.

% carbon does not include carbon present as carbon dioxide.

* Insufficient sample for chemical analysis.

Size gradings were obtained by a Coulter Count on material passing a 75 micron sieve.

D_p as defined in Table A.2.3.8.

Table A.2.3.97 Analysis of bulked samples of bed material

Test Series 5

Period		Start of Test 5.1	Test 5.1	End of Test 5.1	Start of Test 5.2	Test 5.2	End of Test 5.2	Start of Test 5.3	End of Test 5.3
Time, min		942	1203 to 2229	2229	2921	2921 to 3789	3789	4716	5042
Sample Ref		1820	1821	1822	1823	1824	1825	1826	1827
Carbon	%	0.1	0	0.1	0.1	0.1	0.6	0.4	0.2
Sulphur	%	2.9	4.3	5.0	5.1	5.5	5.5	8.0	8.4
Carbon dioxide	%	9.0	11.9	12.8	15.7	15.6	16.2	11.6	10.6
Chlorine	%	0.02	0.02	0.02	0.02	0.02	0.02	0.04	0.02
CaO	%	19.6	25.9	29.0	32.1	33.2	35.6	32.2	32.7
MgO	%	1.6	1.8	1.4	1.7	2.7	1.8	9.5	9.9
Na_2O	%	0.5	0.4	0.4	0.4	0.3	0.3	0.4	0.5
K_2O	%	2.0	1.3	1.1	0.7	0.6	0.6	0.4	0.4
Sulphite sulphur	%	-	<0.01	-	-	<0.01	-	-	<0.01
Sulphide sulphur	%	-	0.1	-	-	0.05	-	-	0.1
Sulphate sulphur	%	-	4.2	-	-	5.45	-	-	8.3
Size grading		% within stated size range							
-1588 +794	μm	29	28	35	29	29	33	37	42
- 794 +500	μm	25	28	23	25	23	26	26	30
- 500 +251	μm	28	31	29	33	31	30	27	23
- 251 +152	μm	14	12	12	12	16	10	10	5
- 152 + 75	μm	2	1	1	1	1	1	0	0
- 75 + 0	μm	2	0	0	-	0	0	0	-
Median diameter,	μm	550	560	580	540	520	600	640	720
Mean diameter, D_p,	μm	360	430	450	430	410	460	490	570

Analyses are given as weight percent on an 'as received' basis.
% carbon does not include carbon present as carbon dioxide.
D_p as defined in Table 3.8.

Table A.2.3.98 Analysis of bed material (other than bulked samples)

Test Series 5

Sample time, min	694	2424	2556	2689	2802	3980	4174	4400	4551	4653	5866	6000
Sample ref	1808	1809	1810	1811	1812	1813	1814	1815	1816	1817	1818	1819
CaO	15.5	29.9	30.2	31.6	32.2	34.6	34.1	32.4	31.7	32.0	31.0	30.0
MgO	1.5	1.0	1.4	1.1	1.4	2.3	4.0	5.6	6.7	8.0	12.4	13.7
Sulphur	5.9	13.3	13.2	13.4	13.8	14.7	16.3	16.8	17.9	19.0	24.2	25.8
Size grading	% within stated size range											
-794 +500 μm	26	27	24	26	23	35	24	27	25	29	28	30
-500 +251 μm	27	31	31	32	30	32	31	29	27	26	24	23
-251 +152 μm	12	11	14	12	15	11	13	8	9	6	6	3
-152 + 0 μm	3	1	1	1	1	1	0	0	0	0	0	0
Median diameter μm	590	570	550	550	540	550	570	630	660	680	710	740
Mean diameter D_p μm	450	500	490	490	480	470	510	590	600	650	690	780

Analyses are given as weight percent on an 'as received' basis.

D_p as defined in Table A.2.3.8.

Table A.2.3.99 Gas composition measurements

Test Series 5

Test No.		5.1	5.2	5.3
Elapsed time from start of Test Series	Start, h	16.2	48.1	78
	End, h	39.2	64.1	86.2
Operating conditions	Ca/S mol ratio	1.87	2.38	1.08
	Variable parameters	Limestone 18	Limestone 18	Dolomite 1337
Gas composition % by volume (dry gas)	CO_2	15.0	14.6	14.2
	CO	0.015	0.01	0.015
	O_2	3.6	3.8	5.3
Gas composition p.p.m. by volume (dry gas)	SO_2	690	470	310
	NO_X	90	90	140
	Cl	30	50	50
	Na_2O	2.1	3.7	0.9
	K_2O	1.0	1.3	0.3

Test Series 5

Oxygen in combustion products:

Test No.	% of test in stated range					Mean Oxygen %
	< 1%	1-2%	2-4%	4-6%	> 6%	
5.1	1	2	58	25	4	3.6
5.2	0	5	53	39	3	3.8
5.3	0	0	10	73	17	5.3

Carbon monoxide in combustion products:

Test No.	% of test in stated range			Mean CO %
	0 to 0.01%	0.01 to 0.02%	> 0.02%	
5.1	31	62	7	.015
5.2	65	32	3	.01
5.3	37	27	36	.015

Table A.2.3.101 Variation of temperature in bed and freeboard

Test Series 5

Height above distributor	Test No.	% of time in stated temperature range					Mean temperature °F
		<1400°F	1400 to 1436°F	1436 to 1472°F	1472 to 1508°F	>1508°F	
Bed 1¼ in to 5 in	5.1 5.2 5.3	2 1 0	12 8 12	55 66 62	30 25 26	1 0 0	1460 1460 1460
Bed 13 in to 16 in	5.1 5.2 5.3	1 1 0	8 5 6	52 62 52	37 31 50	2 1 2	1465 1465 1470
Bed 36 in	5.1 5.2 5.3	1 0 0	2 1 0	18 18 8	62 74 74	17 7 18	1485 1485 1495
Freeboard 77 in	5.1 5.2 5.3	1 0 2	8 0 32	11 1 52	42 34 14	38 65 0	1490 1515 1450
Freeboard 107 in	5.1 5.2 5.3	12 0 22	47 33 49	31 44 29	9 22 0	1 1 0	1430 1450 1420

Table A.2.3.102 Measurement of SO_2 in exhaust gases (Cont'd)

Test Series 5

Time from start,min	SO_2 p.p.m. (v/v)	Time from start,min	SO_2 p.p.m. (v/v)
4190-4210	430	5080-5110	310
4210-4240	410	5110-5140	300
4240-4270	390	5140-5170	310
4270-4300	420	5170-5200	320
4300-4330	480	5200-5230	350
4330-4360	440	5230-5260	370
4360-4390	430	5260-5290	360
4420-4450	380	5290-5320	360
4450-4480	400	5320-5350	370
4480-4510	375	5380-5410	330
4540-4570	360	5410-5440	350
4570-4600	370	5440-5470	360
4600-4630	380	5470-5500	390
4630-4660	400	5500-5530	380
4660-4690	290	5530-5560	390
4690-4720	310	5560-5590	400
4720-4750	320	5590-5620	400
4750-4780	290	5620-5650	420
4780-4870	310	5650-5680	440
4870-4840	310	5680-5710	410
4840-4870	330	5710-5740	500
4870-4900	330	5740-5770	440
4900-4930	310	5770-5800	470
4930-4960	320	5800-5830	470
4960-4990	310	5860-5890	480
4990-5020	310	5890-5920	530
5020-5050	310	5950-5980	470

Note: The SO_2 values quoted are the averaged values from the Hartmann-Braun infra red analyser output for the time intervals stated.

Table A.2.3.102 Measurement of SO_2 in exhaust gases

Test Series 5

Time from start, min	SO_2 p.p.m. (v/v)	Time from start, min	SO_2 p.p.m. (v/v)
320-350	650	2420-2450	590
350-380	700	2450-2480	560
380-410	700	2480-2510	500
410-440	700	2510-2540	510
440-470	650	2540-2570	490
470-500	600	2570-2600	490
500-530	600	2600-2630	500
530-560	670	2630-2660	480
560-590	600	2660-2690	550
590-620	650	2690-2720	600
620-650	600	2720-2750	570
650-680	625	2750-2780	600
680-710	660	2780-2810	560
710-740	620	2810-2840	560
740-770	620	2960-2990	490
770-800	600	2990-3020	440
800-830	580	3020-3050	440
980-950	520	3050-3080	440
950-980	700	3080-3110	420
980-1010	640	3110-3140	440
1010-1040	690	3140-3170	480
1040-1070	700	3170-3200	530
1070-1100	710	3200-3230	640
1100-1130	730	3230-3260	530
1130-1160	750	3260-3290	470
1160-1190	790	3290-3320	490
1190-1220	770	3320-3350	460
1220-1250	760	3350-3380	490
1250-1280	680	3380-3410	420
1280-1310	640	3410-3440	440
1310-1340	610	3440-3470	470
1340-1370	490	3470-3500	520
1370-1400	600	3500-3530	520
1400-1430	570	3530-3560	460
1430-1460	610	3560-3590	450
1460-1490	630	3590-3620	390
1490-1520	620	3620-3650	450
1820-1850	700	3650-3680	460
1850-1880	650	3710-3740	430
1910-1940	750	3740-3770	440
1940-1970	730	3770-3800	460
1970-2000	750	3800-3830	460
2000-2030	720	3830-3860	470
2030-2060	700	3920-3950	510
2060-2090	720	3950-3980	530
2090-2120	710	3980-4010	510
2180-2210	680	4010-4040	520
2210-2240	710	4040-4070	500
2240-2270	760	4070-4100	500
2270-2300	720	4100-4130	410
2300-2330	800	4130-4160	420
2360-2390	570	4160-4190	410

Table A.2.3.103 Comparison of measurements of SO_2 by infra-red and chemical method

Test Series 5

Sample No.	Chemical Method SO_2 p.p.m.	Av. from IR SO_2 p.p.m	Max/min on IR chart SO_2 p.p.m
5	600	650	555/770
6	600	580	480/815
7	695	730	420/920
8	690	680	600/760
9	710	780	675/910
10	600	620	420/780
11	595	570	550/590
15	600	720	620/850
16	645	780	540/845
17	670	740	610/825
18	470	530	440/665
19	440	500	395/740
21	710	610	450/900
22	385	450	350/550
23	410	500	470/535
24	410	470	425/530
25	465	420	305/590
26	470	515	435/650
27	430	495	440/520
28	430	460	310/600
29	380	430	363/545
30	335	405	340/470
31	365	405	370/480
33	260	280	205/330
34	330	315	215/450
35	320	335	260/535
36	340	370	330/410
37	380	455	405/510
38	354	440	330/510
39	385	460	375/540
40	400	465	450/495

Table A.2.3.104 Percentage retention of sulphur, alkalis and chlorine

Test Series 5

Test No.	5.1	5.2	5.3
Stoichiometric ratio	1.87	2.38	1.08
Total Ca/S mole ratio	2.03	2.54	1.24
Per cent retention			
Sulphur	67.2	78.9	84.7
Sodium	98.1	96.8	98.8
Potassium	98.3	98.3	99.4
Chlorine	12.5	12.6	20.7
Per cent reduction			
Sulphur emission	66.1	76.8	84.6

% Retention of sulphur, sodium and potassium
= 100 (total input-output in gas)/total input

% Retention of chlorine
= 100 (total output-output in gas)/total output

% Reduction of sulphur emission
= 100 (emission without acceptor - emission observed)/(emission without acceptor)

Emission without acceptor assumed to be 2032 p.p.m. v/v in dry gas

Stoichiometric ratio assumed = (total Ca/S mole ratio - 0.16)

For Test 5.3, % retention of chlorine calculated as for % retention of sulphur and alkalis

Table A.2.3.105 Concentration of NO_x in combustion gases

Test Series 5

Time from start min	NO_x concentration p.p.m. (v/v)	Method
1530	88	Modified Saltzman
1555	89	"
3010	85	Saltzman
3020	94	"
4470-4490	130	"
4490-4510	137	"
5860-5880	101	"
5880-5900	96	"

Table A.2.3.106 Determinations of alkalis and chlorine in flue gas

Test Series 5

Time from start, h	Concentration, µg/l dry gas			Concentration, p.p.m. by volume, dry gas		
	Cl	Na_2O	K_2O	C_1	Na_2O	K_2O
30.13	19	3.1	1.4	12	1.1	0.3
35.74	82	8.4	6.7	52	3.0	1.6
61.20	72	10.2	5.4	45	3.7	1.3
83.42	78	2.8	0.9	49	1.0	0.2
88.85	83	2.3	1.4	53	0.8	0.3
100.00	-	2.5	1.7	-	0.9	0.4

Table A.2.3.107 Mass Balances for Test 5.1

Test Series 5

Flow Rates in lb/h

	Total	Ash	Carbon	Hydrogen	Nitrogen	Oxygen
Inputs						
Coal	467	60.8	333.3	22.48	7	31
Limestone	80	50.3	8.0	0.01	-	21
Main Air	4813	-	0.6	1.04	3688	1124
Conveying Air	431	-	0.1	-	331	100
Dipleg Nitrogen	19	-	-	-	19	-
Total Input	5811	111.2	342.0	23.53	4045	1277
Outputs						
Gained by Bed	9	0.2	1.0	-	-	6
Weir Solids	20	15.5	0.6	-	-	3
Primary Cyclone	100	76.8	6.0	-	-	12
Secondary Cyclone	2	1.3	0.0	-	-	0
Exhaust Dust	1	1.1	0.0	-	-	0
Flue Gas	5679	-	320.6	23.53	4083	1247
Total Outputs	5811	95.0	328.3	23.53	4083	1269

	Sulphur	Calcium	Magnesium	Sodium	Potassium	Chlorine
Inputs						
Coal	12.03	4.34	0.723	0.652	0.729	0.383
Limestone	-	26.22	0.433	0.237	0.066	-
Main Air	-	-	-	-	-	-
Conveying Air	-	-	-	-	-	-
Dipleg Nitrogen	-	-	-	-	-	-
Total Input	12.03	30.56	1.156	0.889	0.796	0.383
Outputs						
Gained by Bed	2.03	6.79	-0.150	-0.025	-0.440	0.002
Weir Solids	0.86	3.71	0.218	0.059	0.216	0.004
Primary Cyclone	4.33	17.11	0.546	0.448	0.835	0.020
Secondary Cyclone	0.07	0.12	0.011	0.008	0.021	0.000
Exhaust Dust	0.08	0.11	0.010	0.007	0.018	0.003
Flue Gas	3.94	-	-	0.017	0.014	0.202
Total output	11.31	27.84	0.635	0.515	0.664	0.230

Bed compositions interpolated from smoothed plots versus time.
Flow rate of primary cyclone solids assessed by dry sampling method.
Hydrogen contents of primary and secondary cyclone solids assumed to be due to moisture absorbed after weighing, and the analyses have been corrected to the dry basis.
Alkali and Alkali earth contents of exhaust dust assumed to be equal to those of secondary cyclone solids.

Table A 2.3.108 Mass Balances for Test 5.2

Test Series 5

Flow rates in lb/h

	Total	Ash	Carbon	Hydrogen	Nitrogen	Oxygen
Inputs						
Coal	477	64.4	334.4	22.54	7	35
Limestone	113	71.6	11.4	0.01	-	30
Main Air	4895	-	0.6	1.30	3749	1144
Conveying Air	435	-	0.1	-	334	101
Dipleg Nitrogen	19	-	-	-	19	-
Total Input	5939	136.0	346.5	23.85	4109	1310
Outputs						
Gained by Bed	-	-1.7	0.7	-	-	1
Weir Solids	61	42.7	2.7	-	-	12
Primary Cyclone	98	72.9	4.5	-	-	15
Secondary Cyclone	2	1.4	0.0	-	-	0
Exhaust Dust	4	2.7	0.1	-	-	0
Flue Gas	5775	-	317.9	23.85	4171	1260
Total Output	5940	118.0	325.9	23.85	4171	1288
	Sulphur	**Calcium**	**Magnesium**	**Sodium**	**Potassium**	**Chlorine**
Inputs						
Coal	12.98	3.90	0.960	0.633	0.99	0.413
Limestone	-	37.28	0.616	0.337	0.09	-
Main Air	-	-	-	-	-	-
Conveying Air	-	-	-	-	-	-
Dipleg Nitrogen	-	-	-	-	-	-
Total Input	12.98	41.18	1.576	0.970	1.08	0.413
Outputs						
Gained by Bed	0.23	2.62	0.207	-0.085	-0.10	-
Weir Solids	3.33	14.37	0.986	0.135	0.30	0.012
Primary Cyclone	4.84	20.10	0.774	0.439	0.57	0.020
Secondary Cyclone	0.09	0.16	0.013	0.013	0.02	0.000
Exhaust Dust	0.28	0.35	0.029	0.027	0.05	0.010
Flue Gas	2.74	-	-	0.031	0.02	0.293
Total Output	11.50	37.60	2.009	0.560	0.86	0.335

Bed compositions interpolated from smoothed plots versus time.
Flow rate of primary cyclone solids assessed by dry sampling method.
Hydrogen contents of primary and secondary cyclone solids assumed to be due to moisture absorbed after weighing, and the analyses have been corrected to the dry basis.
Alkali and alkali earth contents of exhaust dust assumed to be equal to those of seconadry cyclone solids.

Table A.2.3.109 Mass Balances for Test 5.3

Test Series 5

Flow Rates in lb/h

	Total	Ash	Carbon	Hydrogen	Nitrogen	Oxygen
Inputs						
Coal	451	49.49	321.5	21.93	5	40
Dolomite	81	42.16	10.5	0.00	-	28
Main Air	5029	-	0.6	1.23	3852	1175
Conveying Air	453	-	0.1	-	348	105
Dipleg Nitrogen	19	-	-	-	19	-
Total Input	6033	91.64	332.7	23.16	4224	1349
Outputs						
Gained by bed	2	0.01	-1.1	-	-	1
Weir Solids	18	11.90	0.6	-	-	4
Primary Cyclone	82	60.48	4.5	-	-	12
Secondary Cyclone	1	1.31	0.0	-	-	0
Exhaust Dust	1	0.70	0.0	-	-	0
Flue Gas	5929	-	319.5	23.16	4231	1353
Total Output	6033	74.41	323.6	23.16	4231	1370
	Sulphur	Calcium	Magnesium	Sodium	Potassium	Chlorine
Inputs						
Coal	12.22	1.07	-0.06	0.395	0.308	0.426
Dolomite	0.02	17.88	10.13	0.240	0.402	-
Main Air	-	-	-	-	-	-
Conveying Air	-	-	-	-	-	-
Dipleg Nitrogen	-	-	-	-	-	-
Total Input	12.24	18.95	10.06	0.635	0.710	0.426
Outputs						
Gained by bed	1.90	0.98	2.47	0.263	0.007	-0.045
Weir Solids	1.43	4.05	1.02	0.052	0.058	0.005
Primary Cyclone	4.80	13.48	4.49	0.307	0.481	0.017
Secondary Cyclone	0.05	0.09	0.04	0.010	0.020	0.000
Exhaust Dust	0.03	0.05	0.02	0.005	0.011	0.000
Flue Gas	1.87	-	-	0.008	0.004	0.337
Total Output	10.08	18.66	8.05	0.645	0.580	0.314

Bed compositions interpolated from smoothed plots versus time.
Hydrogen contents of Primary and Secondary cyclone solids assumed to be due to Moisture absorbed after weighing, and the analyses have been corrected to the dry basis.
Composition of Exhaust Dust assumed to be equal to that of the Secondary Cyclone solids.

Table A.2.3.110 Heat Balances, million Btu/h

Test Series 5

Test No.	5.1	5.2	5.3
Heat Inputs			
In coal-acceptor mixture, total	5.92	5.99	5.75
In air and nitrogen, total	0.05	0.06	0.06
Heat of sulphation of $CaCO_3$	0.04	0.04	0.04
Total Heat Input	6.01	6.09	5.85
Heat Outputs			
Weir solids, total	0.01	0.03	0.01
Elutriated solids, sensible	0.04	0.04	0.03
potential	0.06	0.02	0.04
Cyclone and weir blowdowns, total	0.05	0.05	0.05
Exhaust flue gas, sensible	2.05	2.10	2.12
potential	0.00	0.00	0.00
latent	0.22	0.23	0.22
To water cooling, in bed	3.25	3.26	3.01
in freeboard	0.23	0.20	0.26
shell cooling	0.09	0.09	0.09
To shell pressurising air	0.02	0.02	0.02
Estimated radiation losses	0.01	0.01	0.01
Heat of calcination of $MgCO_3$	0.00	0.00	0.02
Total Heat Output	6.03	6.05	5.88
Unaccounted, (Input-Output)	-0.02	+0.04	-0.03
Unaccounted, % of Input	-0.3	+0.7	-0.5

Total heats are the sums of sensible heat and of potential and/or latent heats.

Sensible heats refer to 32°F datum; the sensible heat of coal-acceptor mixture approx. 0.002 million Btu/h.

Potential heat of coal-acceptor mixture equals that of the coal fed.

Latent heat of water vapour in input gas approx. 0.02 million Btu/h.

Total heat of weir solids includes that due to gain in weight of bed.

Reaction heats calculated assuming the following reaction equations:

$CaCO_3 + SO_2 + \frac{1}{2}O_2 = CaSO_4 + CO_2 + 77.1$ kcal/mole

$MgCO_3 = MgO + CO_2 - 24.2$ kcal/mole

Table A.2.3.111 Weight Losses of Corrosion Specimens - μg/cm^{2}h

Test Series 5

Tube No.	Location of Ring	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t
1	Alloy	N		R	S	N	R	E	S	N	R	S	N	R	E		S	N	R	S	N
	Weight Loss	56	**	***	42	92	118	74	46	70	35	21	33	49	54	**	10	***	24	10	16
	Temperature (°F)		1450													1450					
2	Alloy	W		N	W	E	N	S	R	S	N	W	S	N	R		W	E	N	R	S
	Weight Loss	3	**	4	5	14	7	8	20	4	12	3	3	8	12	**	4	76	24	13	***
	Temperature (°F)		1040													1200					
3	Alloy	F_2		F_1	F_2	F_2	F_2	F_2	F_2	F_1	F_2	F_2	F_2	F_2	F_1		F_2	F_2	F_2	F_2	F_2
	Weight Loss	8	**	19	21	13	18	17	16	28	19	23	32	20	***	**	***	17	29	20	39
	Temperature (°F)		750													840					
4	Alloy	E		F_1	F_2	F_1	N	F_2	F_1	F_2	F_1	F_2	F_1	F_2	F_1		F_2	F_1	F_2	F_1	F_2
	Weight Loss	***	**	82	86	117	***	89	119	115	189	140	165	134	130	**	187	250	243	277	211
	Temperature (°F)		880													950					
5	Alloy	F_2		F_1	F_2	F_1	F_2	F_1	F_2	R	W	F_1	F_2	F_1	F_2		F_1	F_2	F_1	F_2	F_1
	Weight Loss	24	**	44	56	65	71	83	72	***	***	84	133	96	76	**	77	84	93	79	71
	Temperature (°F)		660													880					
6	Alloy	N		R	S	N	R	E	S	N	R	S	N	R	S		E	N	R	S	N
	Weight Loss	24	**	31	19	52	46	***	***	12	23	11	14	30	13	**	49	73	408	60	50
	Temperature (°F)		1450													1450					

** Specimen used for measuring metal temperature

*** Specimen not descaled, retained for further examination

F_1	Ferritic 1%Cr ½Mo steel
F_2	Ferritic 2¼%Cr steel
W	Ferritic 12%Cr steel
S	Austenitic Type 316
R	Austenitic Type 347
E	Austenitic Type Esshete 1250
N	Nimonic PE 16

Table A.2.3.112 Summary of weight losses of corrosion specimens

Test Series 5

Material		Tube 1		Tube 6		Tube 2		Tube 4		Tube 3		Tube 5	
		1450°F	1450°F	1450°F	1450°F	1200°F	1040°F	950°F	880°F	840°F	750°F	880°F	660°F
1% Cr	Av. loss	-	-	-	-	-	-	200	106	28	18	84	64
	Max/Min	-	-	-	-	-	-	277/130	119/82	-	-	93/71	82/64
	No. of Specimens							5	3	1	1	5	3
2¼% Cr	Av. loss	-	-	-	-	-	-	170	88	25	15	93	55
	Max/Min	-	-	-	-	-	-	242/115	89/86	39/17	21/8	133/76	72/24
	No. of Specimens	-	-	-	-	-	-	6	2	8	6	4	4
12% Cr	Av. loss	-	-	-	-	4	4	-	-	-	-	-	-
	Max/Min	-	-	-	-	4/3	5/3	-	-	-	-	-	-
	No. of Specimens	-	-	-	-	2	2	-	-	-	-	-	-
SF316	Av. loss	44	14	19	12	4	8	-	-	-	-	-	-
	Max/Min	46/42	21/10	-	13/11	4/3	-	-	-	-	-	-	-
	No. of Specimens	2	3	1	2	2	1	-	-	-	-	-	-
RF36	Av. loss	118	36	38	26	13	20	-	-	-	-	-	-
	Max/Min	-	49/24	46/31	30/23	13/12	-	-	-	-	-	-	-
	No. of Specimens	1	3	2	2	2	1	-	-	-	-	-	-
Esshete 1250	Av. loss	74	54	-	49	76	14	-	-	-	-	-	-
	Max/Min	-	-	-	-	-	-	-	-	-	-	-	-
	No. of Specimens	1	1	-	1	1	1	-	-	-	-	-	-
PE 16	Av. loss	74	40	38	37	14	6	-	-	-	-	-	-
	Max/Min	92/56	70/16	52/24	50/12	24/8	7/4	-	-	-	-	-	-
	No. of Specimens	2	3	2	4	3	2	-	-	-	-	-	-

Notes:- (1) Under each Tube heading are given the measured metal temperatures at the outlet and inlet of each tube respectively.

(2) The "av. loss" and "max/min" are the weight losses in $\mu g/cm^2h$.

Table A.2.3.113 Metallographic examination of corrosion specimens

Test Series 5

Temp. ^{o}F	Material	Surface Texture	Deposit/ Scale	Penetration, μm	
				Pits	Sulphur
800	F1 F2	smooth smooth	0 0	0 0	0 0
930	F1 F2	smooth smooth	0 0	0 0	0 0
1110	S R N	smooth smooth smooth	0 0 0	0 0 0	v. slight 0 0
1470	S R N	rough rough rough	0 0 0	0 0 0	v. slight 0 v. slight

Table A.2.3.114 Comparison of dust from walls of cascade holder with airborne dust passing over cascade

Test Series 2

	Dust deposited on walls	Exhaust dust
% CaO	11.2	7.7 - 10.5
% MgO	5.6	4.5 - 7.6
% Na_2O	0.8	0.7 - 1.0
% K_2O	1.5	1.6 - 1.9

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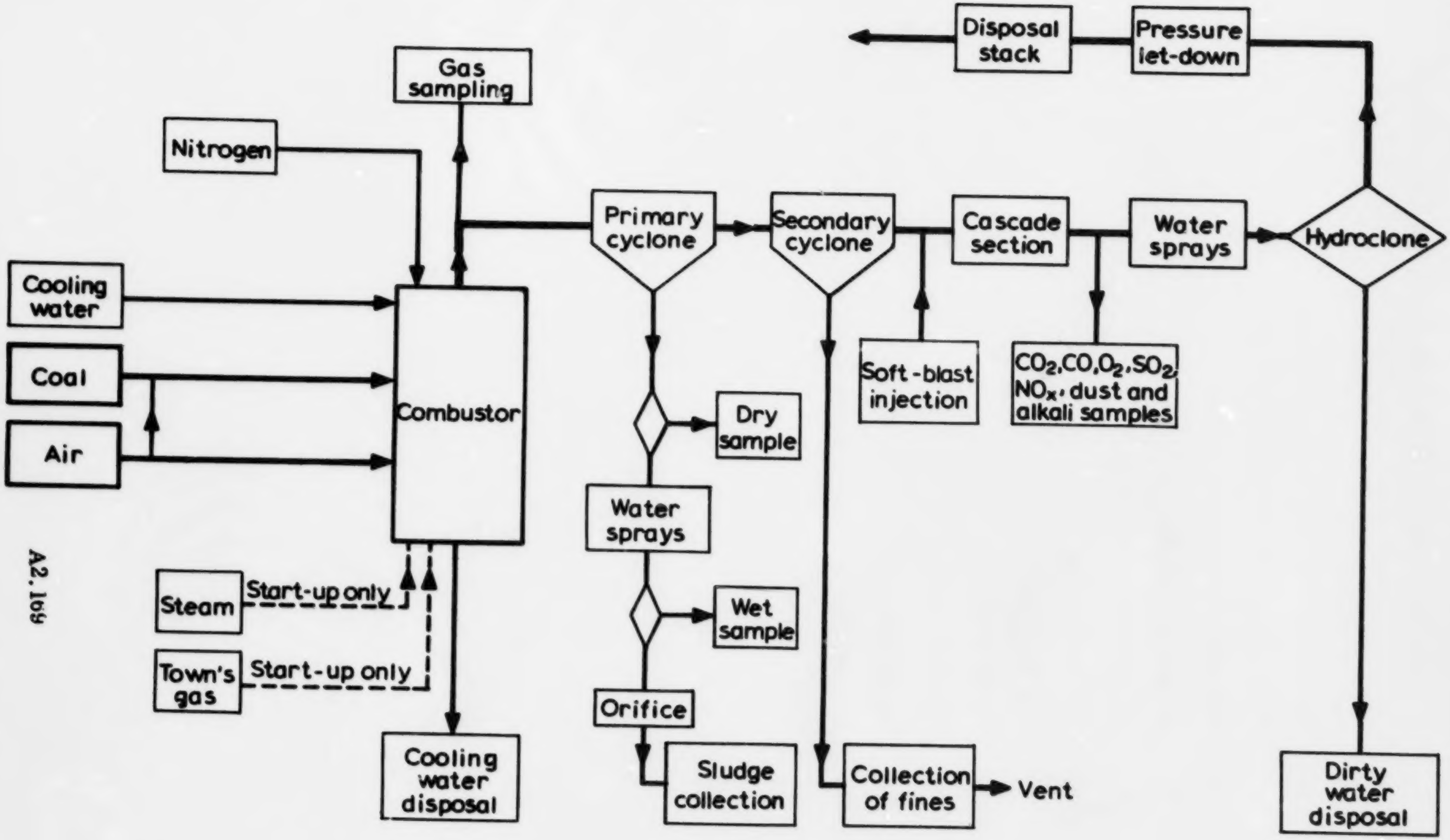


Fig. A2.2.1. Task II. Flow diagram of Pressurized Fluid-bed Combustor

Notes on diagram of 48 in x 24 in pressurised combustor

1. Water supply to water-cooled circuits
2. First-stage dust-collecting cyclone
3. Internal recirculation cyclone
4. Balance air supply
5. Gas burners for start-up
6. Bed removal pipe
7. Pressure shell
8. Cooled liner
9. Combustor casing
10. Second-stage dust-collecting cyclone
11. Air supplies to air preheating tubes and corrosion assemblies
12. Cascade housing
13. Sampling point for alkali content of gases
14. Mixing baffle
15. Sampling point for NO_x gases
16. Spray nozzles
17. Deposition probe (Not used in the APCO programme).
18. Dust sampling and O_2, CO_2, CO, probe
19. Exhaust to pressure let-down valve
20. Dip-leg from recirculation cyclone

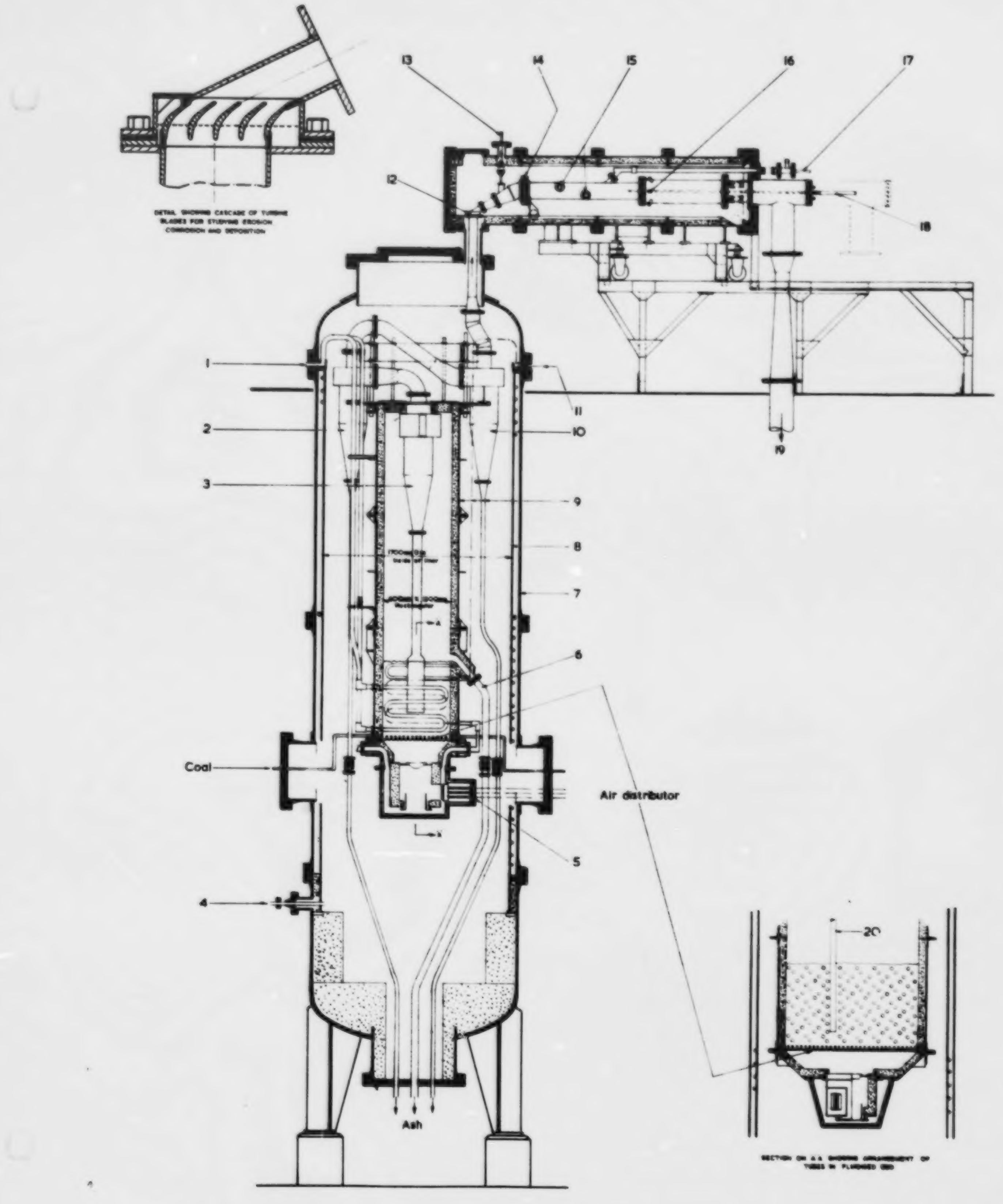
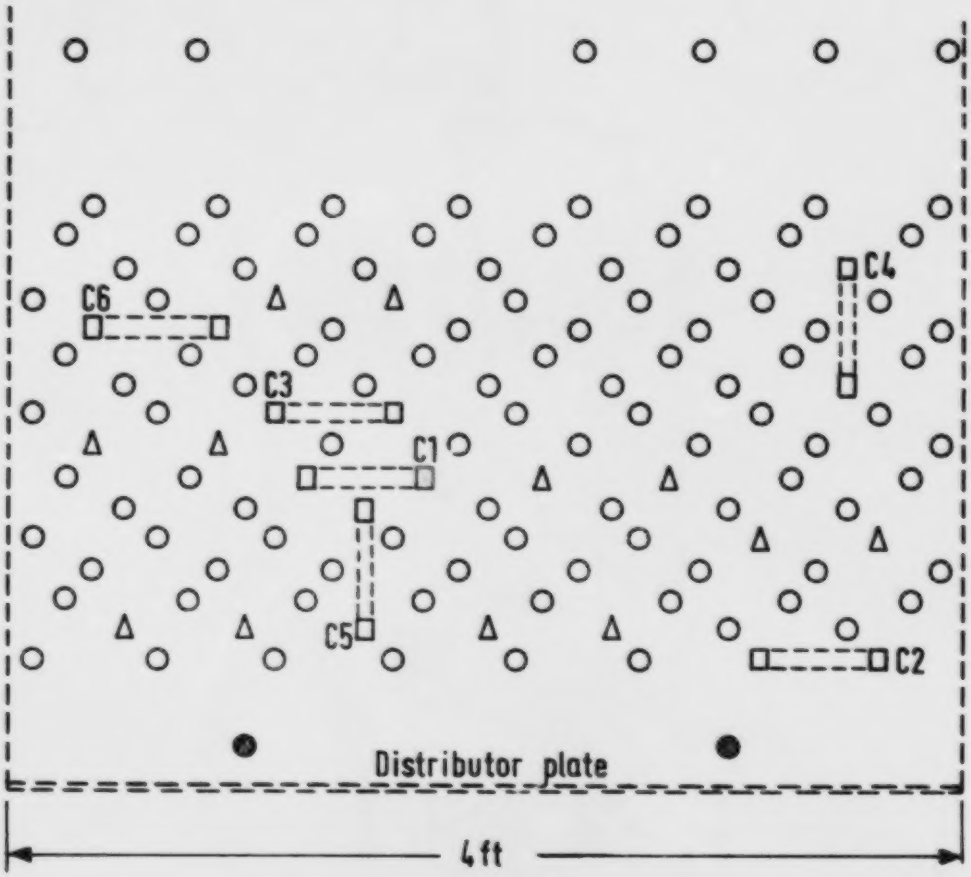

DETAIL SHOWING CASCADE OF TURBINE BLADES FOR STUDYING EROSION CORROSION AND DEPOSITION
13
14
15
16
17
12
18
1
11
2
10
19
3
9
8
7
6
Coal
Air distributor
5
4
Ash
20
SECTION ON A.A SHOWING ARRANGEMENT OF TUBES IN FLUIDISED BED

Fig. A2.22 Task II. 48 x 24 pressurised fluid-bed combustion rig



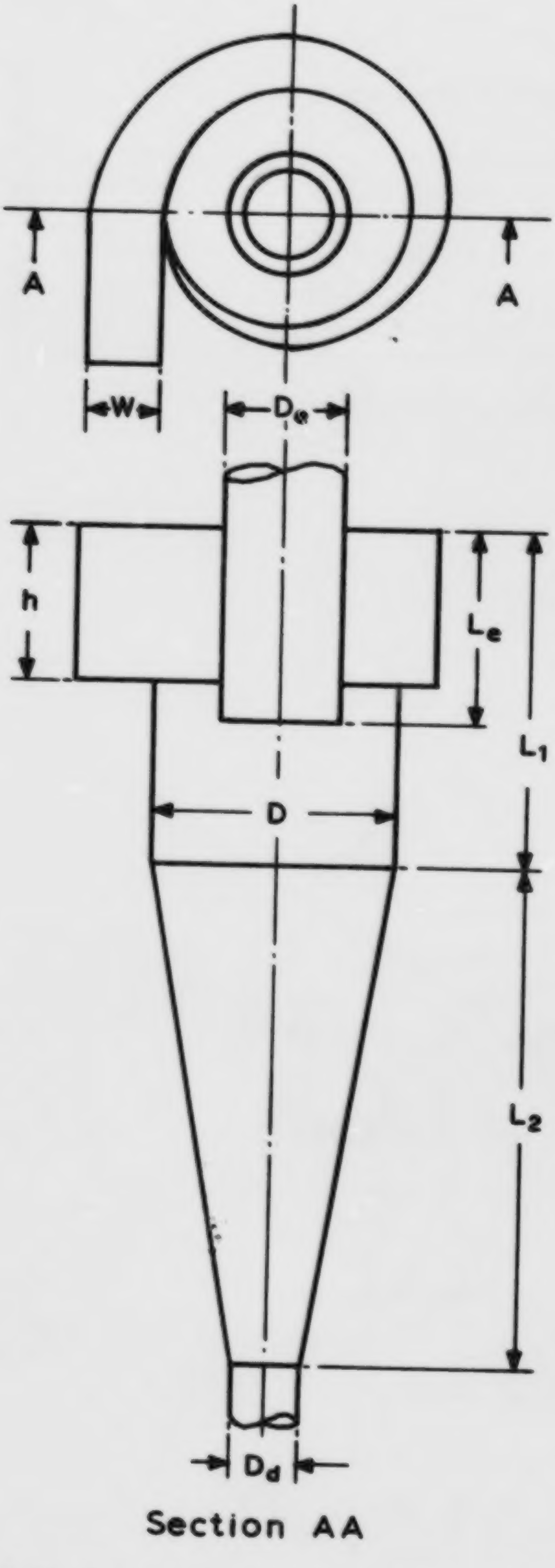
○ Water-cooled circuit or dummy tube

□ Corrosion probes C1 to C6

△ Air-preheating tube

● Coal nozzle

Fig. A2.2.3. Task II. Arrangement of tubes in the bed



Section AA

Fig. A2.2.4. Task II. Key to dimensions of cyclones

(see Table A2.2.1)

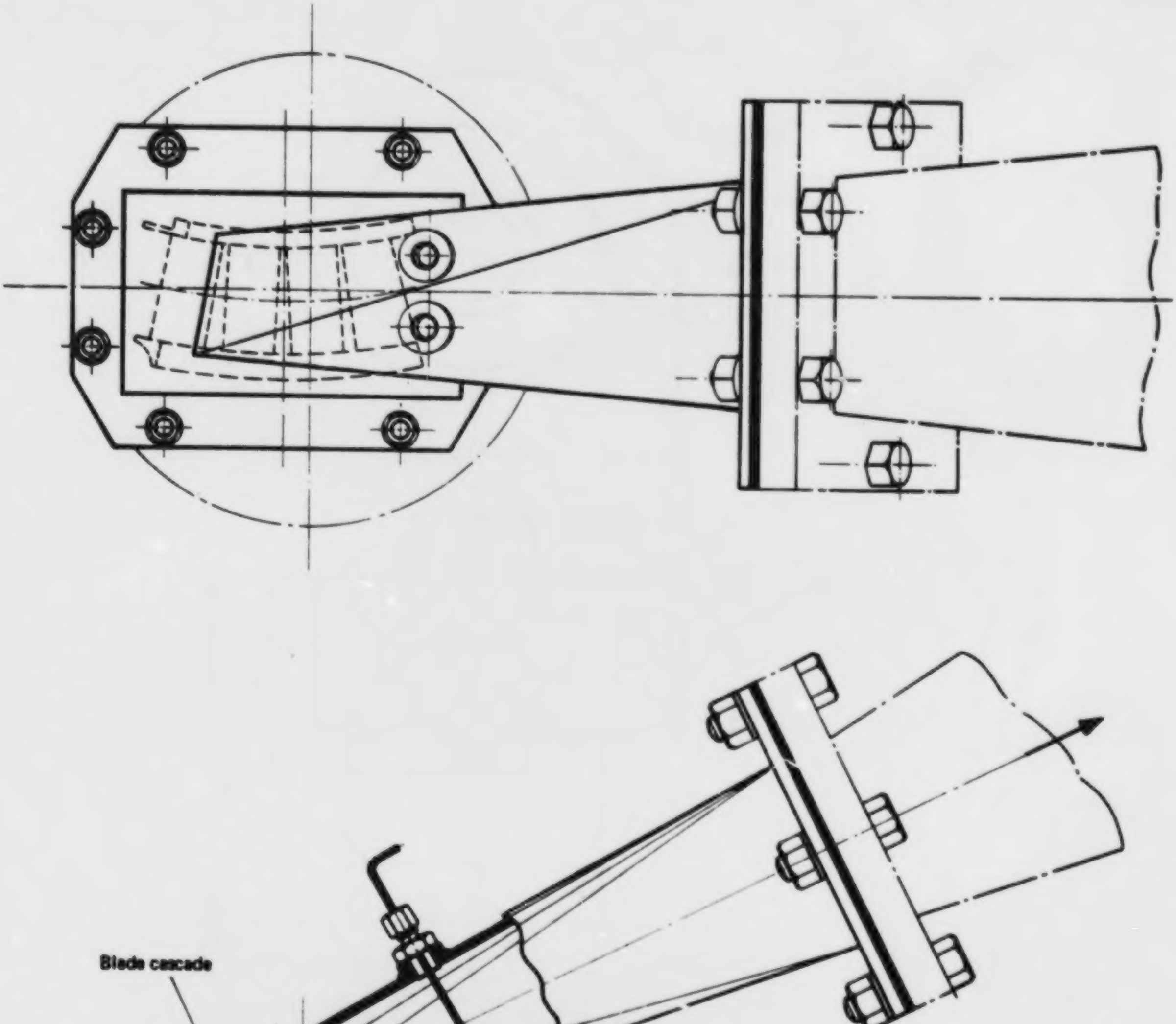


Fig. A2.2.5.

Arrangement of blade cascade and target rods

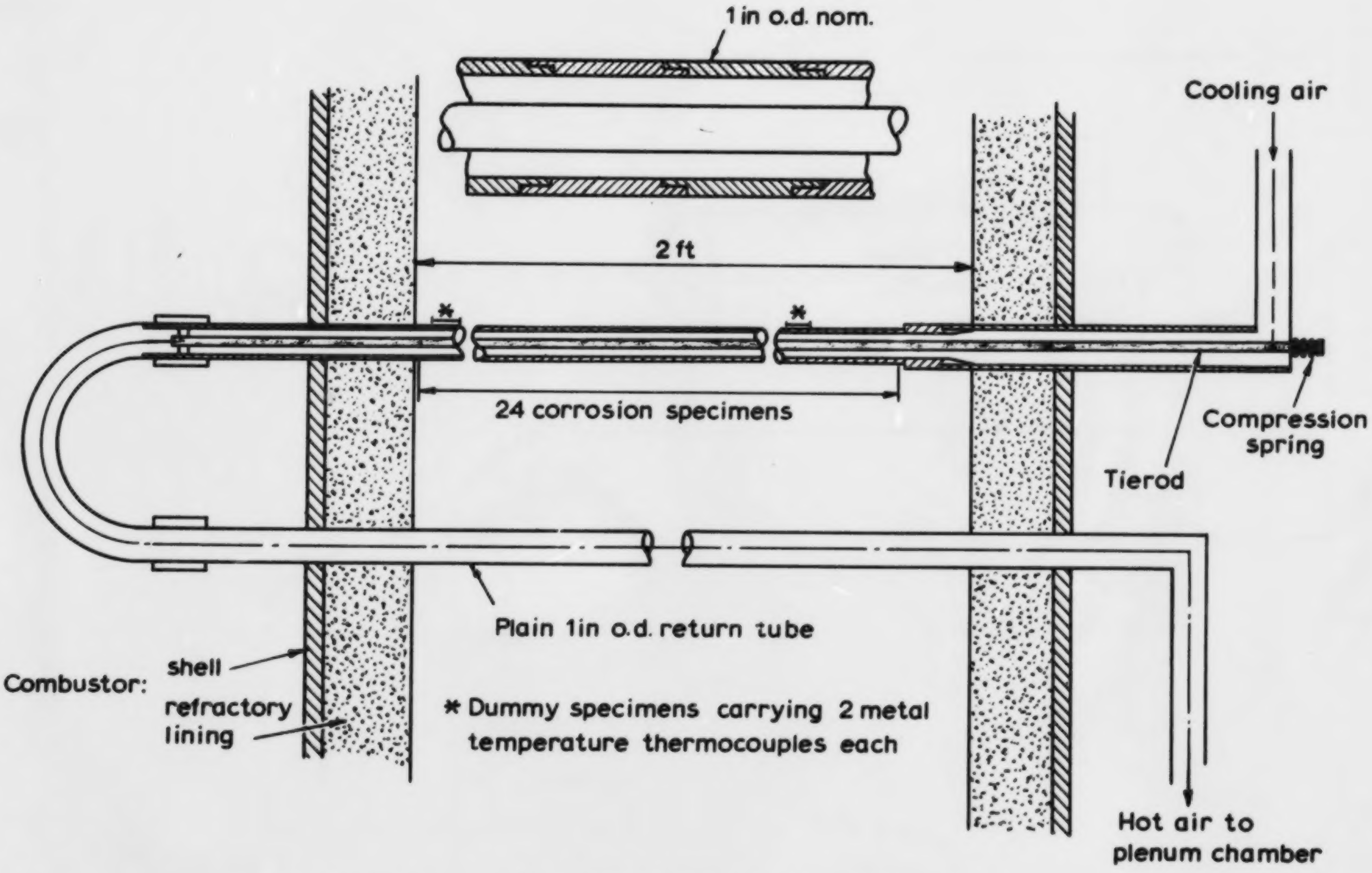

1in o.d. nom.
Cooling air
2 ft
*
*
24 corrosion specimens
Compression spring
Tierod
Plain 1in o.d. return tube
Combustor:
shell
refractory lining
* Dummy specimens carrying 2 metal temperature thermocouples each
Hot air to plenum chamber

Fig.A2.2.6. Task II. Corrosion tube assembly

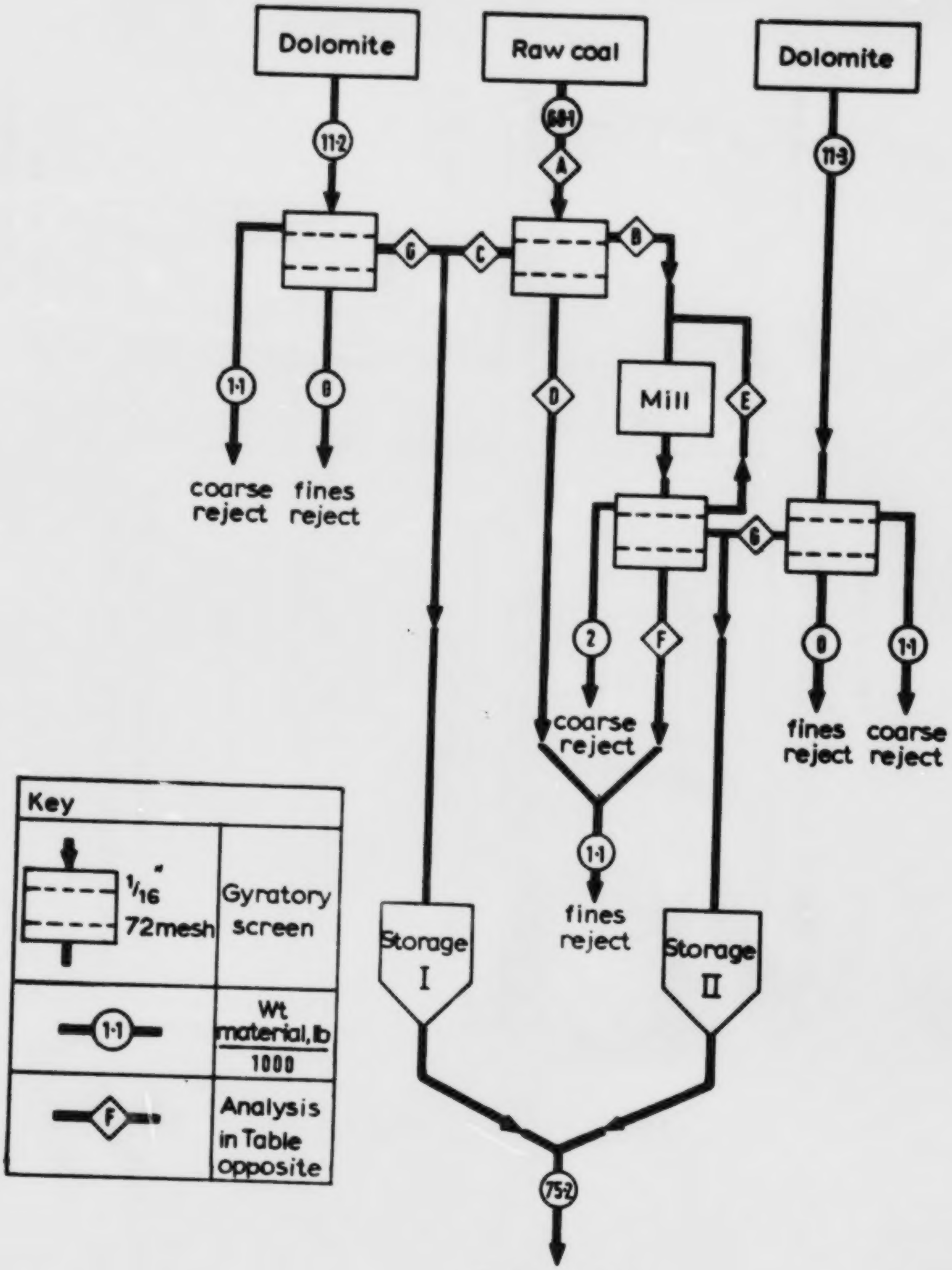


Fig.A2.2.7.Task II. Coal and dolomite preparation

Analysis of Coal and Dolomite for Test Series 2

Sample reference in Fig. A.2.2.7		A	B	C	D	E	F	F
Composition, %								
Moisture		2.8	1.4	1.6	2.9	1.2	1.4	
Volatile Matter		-	34.7	35.4	34.2	33.7	36.9	
Fixed Carbon		-	48.1	51.3	49.1	46.0	48.4	
Ash		-	15.8	11.7	13.8	19.1	13.3	
Sulphur		-	2.8	2.9	3.3	2.6	3.2	
Size Grading								
(% less than stated size)								
¼"	(6350 µm)	95	91		-	99.9	-	
⅛"	(3175 µm)	73	46		-	89	-	
7 BS mesh	(2411 µm)	63	25		-	-	-	
1/16"	(1588 µm)	51	0	100	-	19	-	100
16 BS mesh	(1003 µm)	39		77	-	-	-	-
1/32"	(794 µm)	-		-	-	-	-	25
30 BS mesh	(500 µm)	25		49	-	-	-	7
60 BS mesh	(251 µm)	16		31	99.9	-	-	4
100 BS mesh	(152 µm)	11		21	84	-	89	3
200 BS mesh	(75 µm)	7		13	44	-	56	2

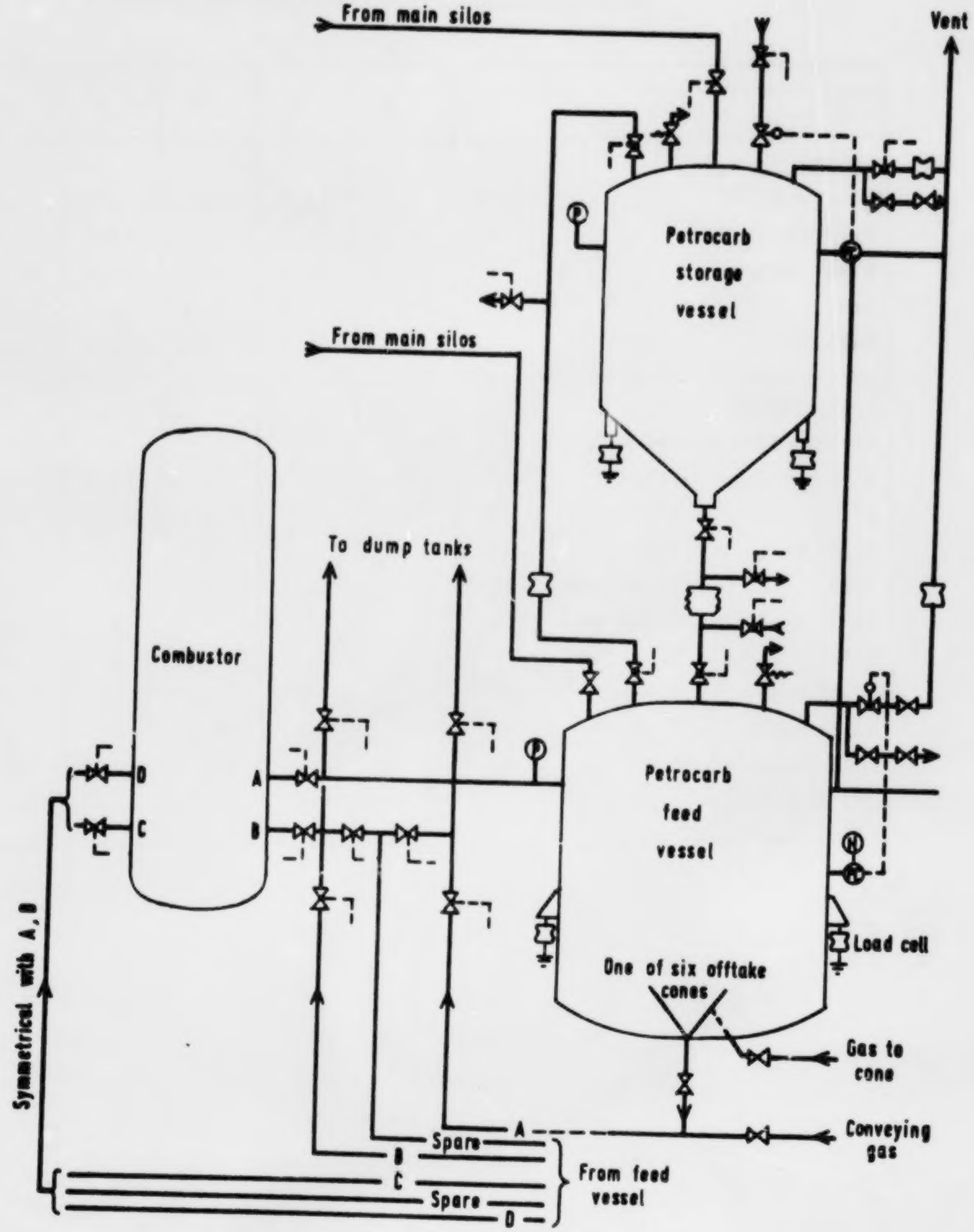
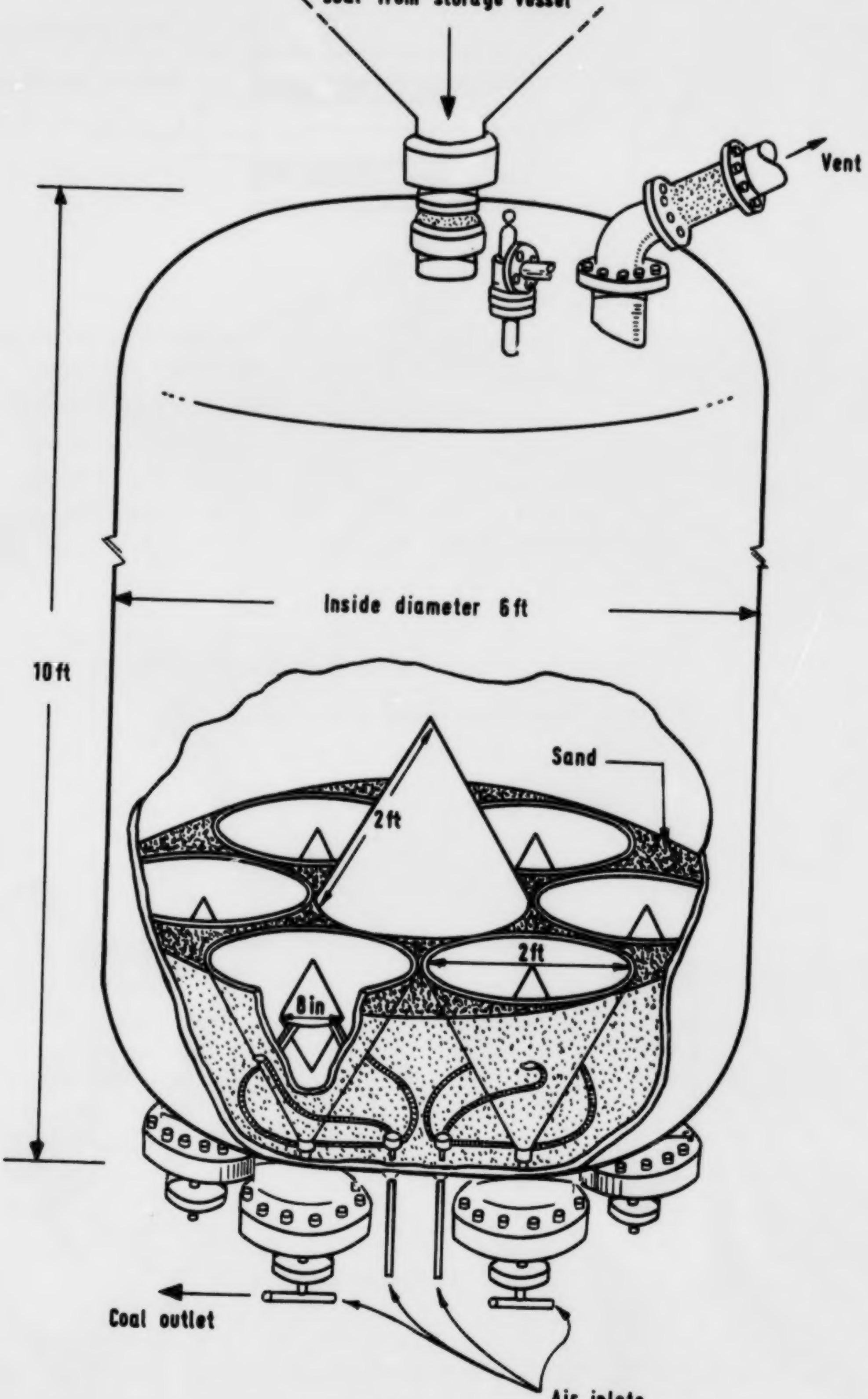
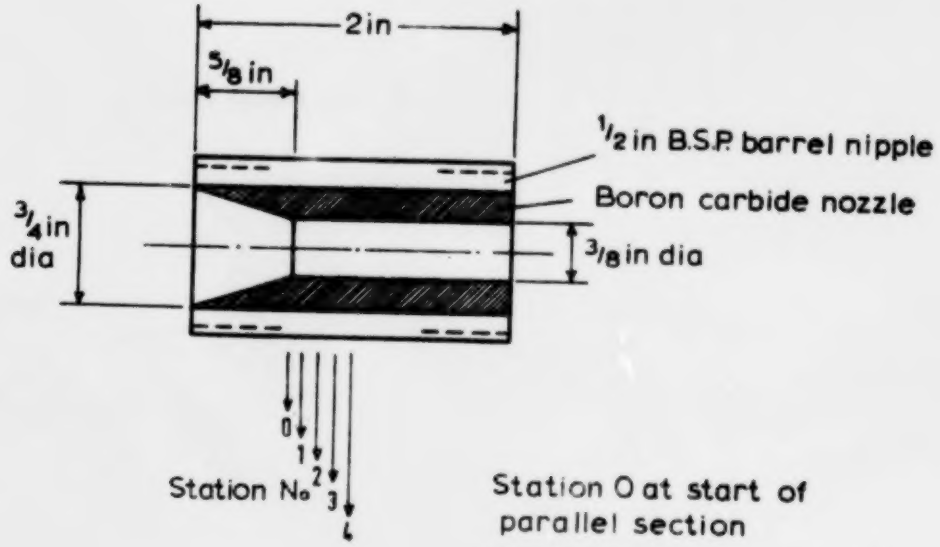


Fig. A2.2.8. Task II. Coal feeding system



A2.179

Fig.A2.2.9. Task II. Arrangement of Petrocarb coal feed vessel



Station 0 at start of parallel section

Station 1 at 2·5mm from 0
" 2 " 5·0mm " 0
" 3 " 7·5mm " 0
" 4 " 10·0mm " 0

Section through nozzle

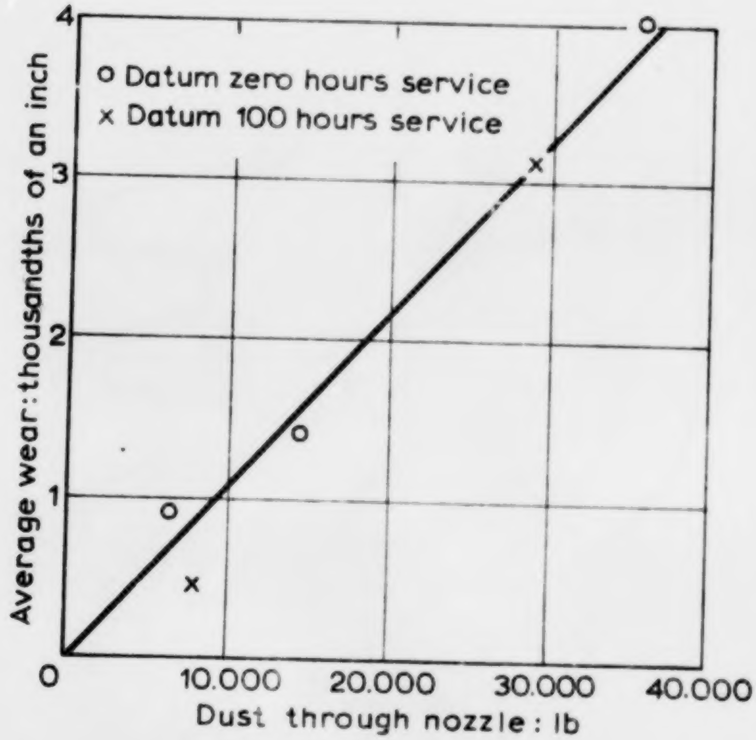


Fig.A2.2.10. Task II. Wear rate of boron carbide nozzle in primary cyclone blowdown

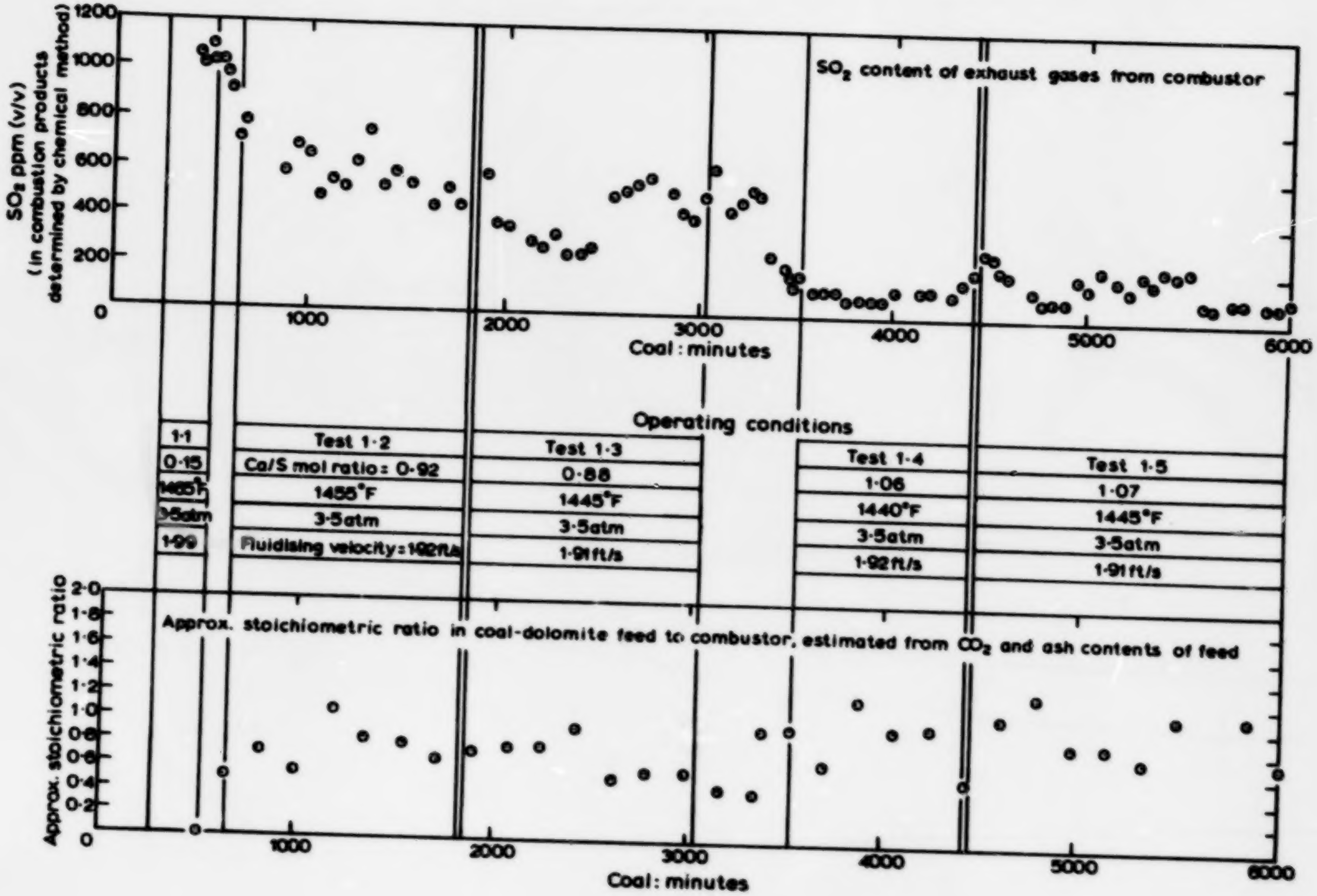


Fig A2. 3.1. Task II. Test Series 1. Ca/S ratio and retention of SO_2 versus time

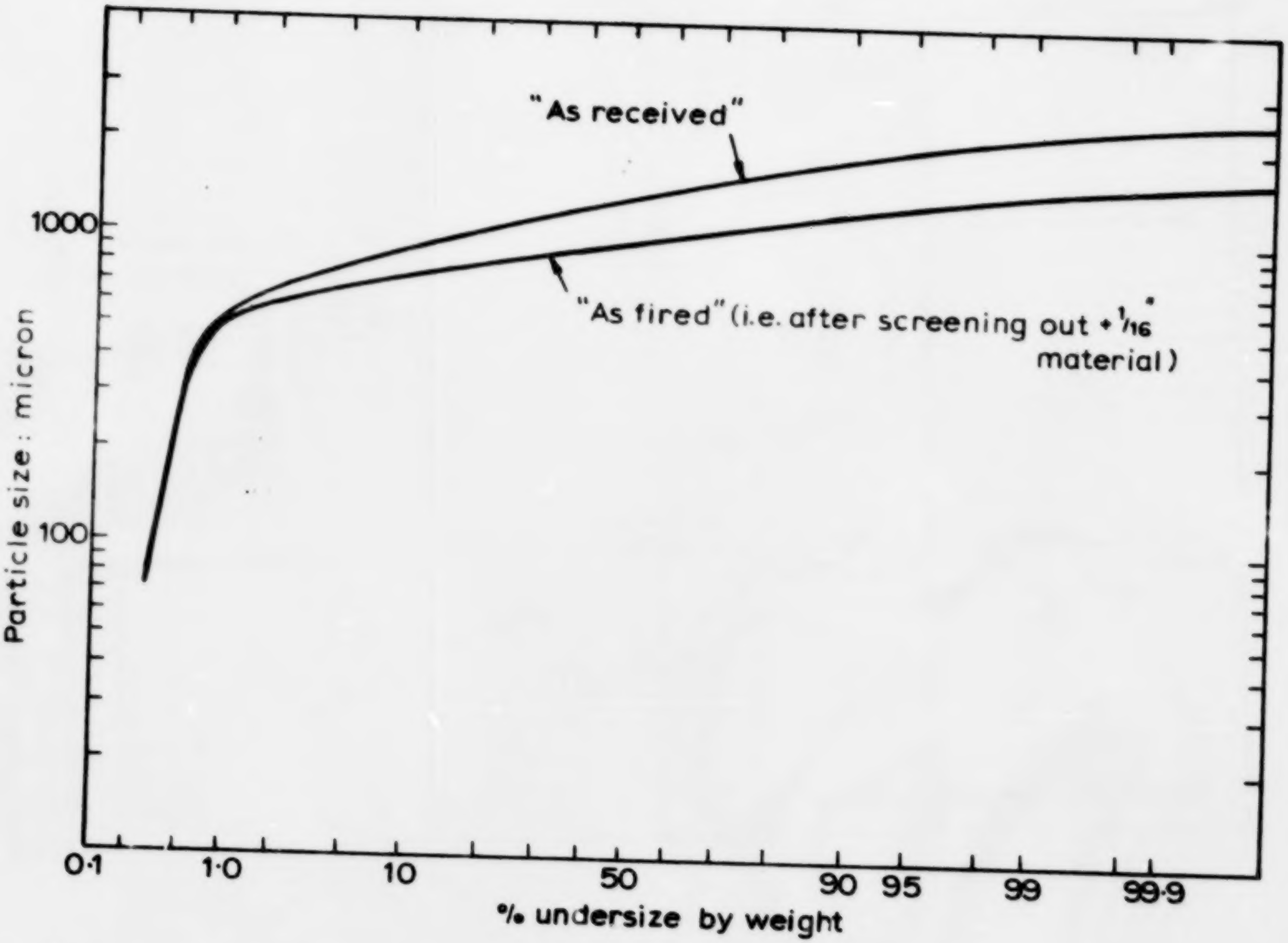
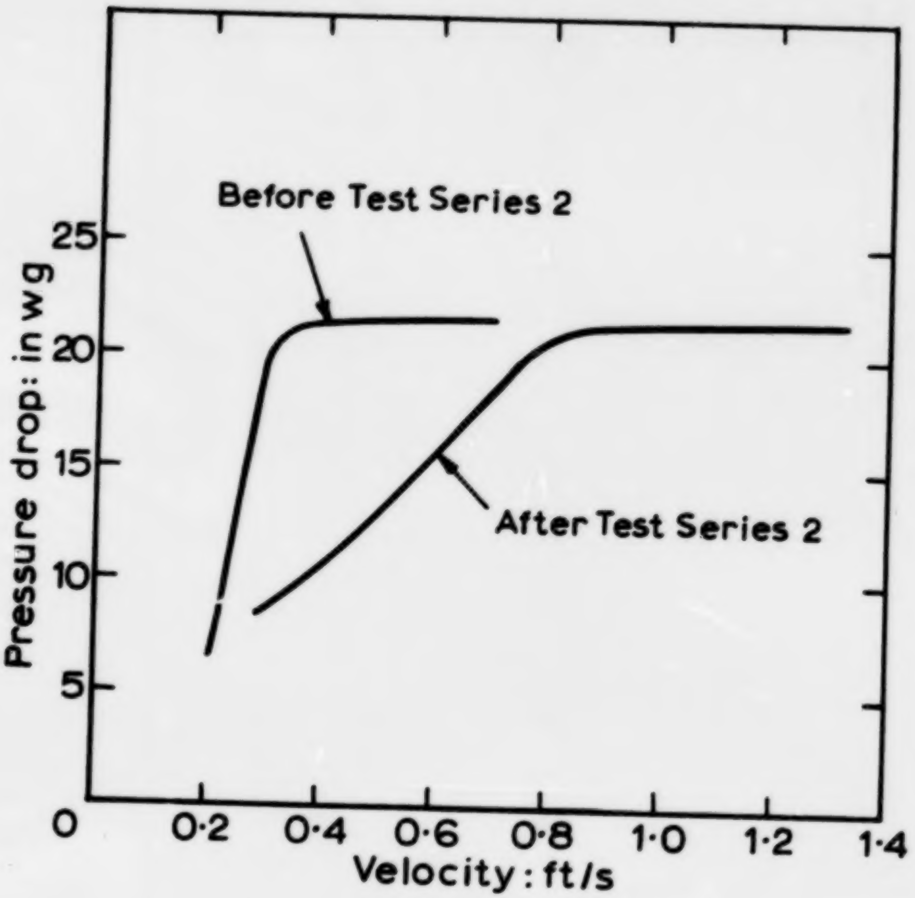


Fig.A2.3.2. Task II. Size distribution of dolomite used in Test Series 2 and 3



Fluidised in a 12 in dia vessel using cold air at atmospheric pressure

Bed height (static) c.18 in

Expansion c.12%

Fig. A2.3.3. Task II. Fluidising characteristics of bed material before and after Test Series 2

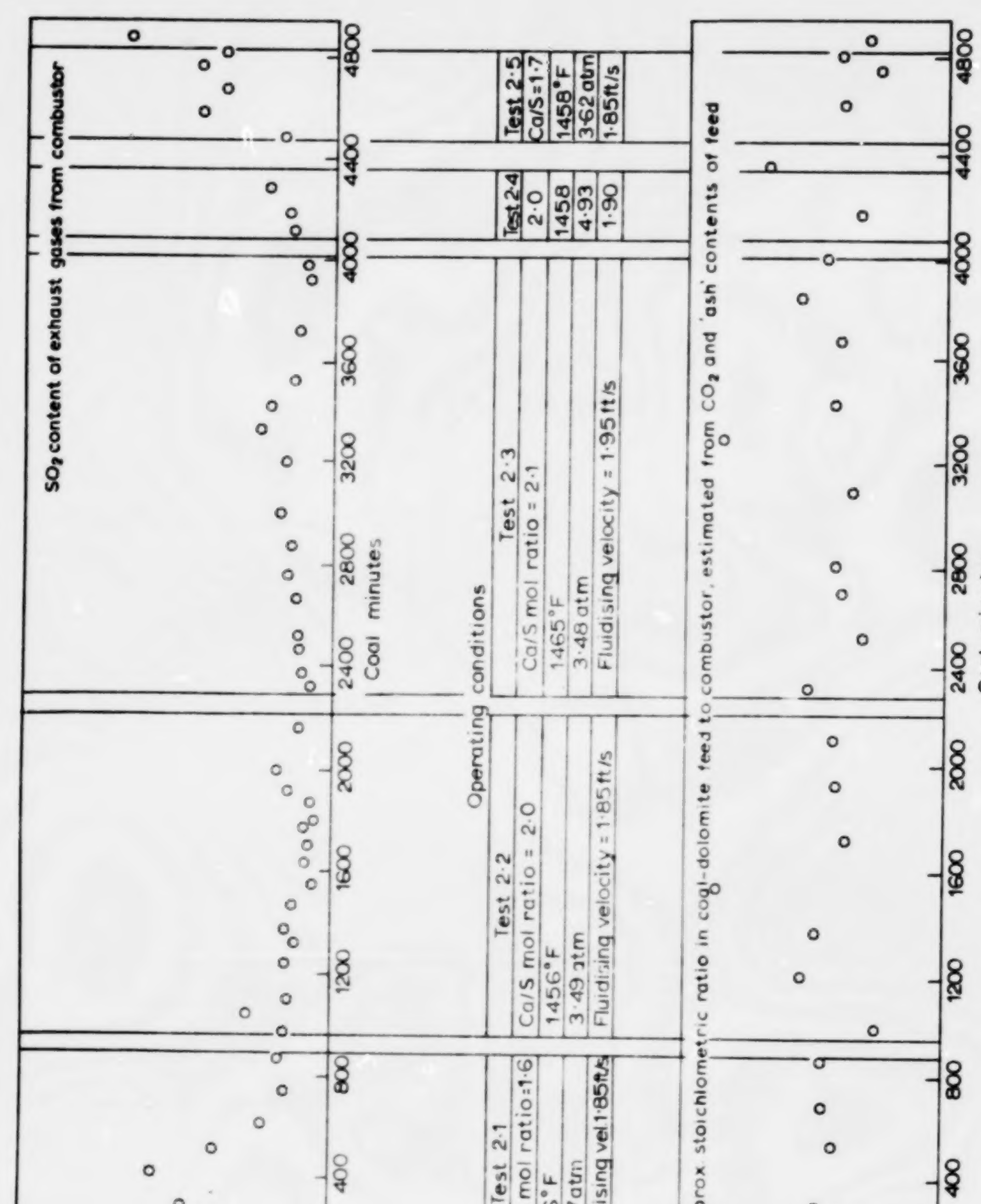


Fig.A2.3.4. Task II. Test series 2. Ca/S ratio and retention of SO₂ versus time

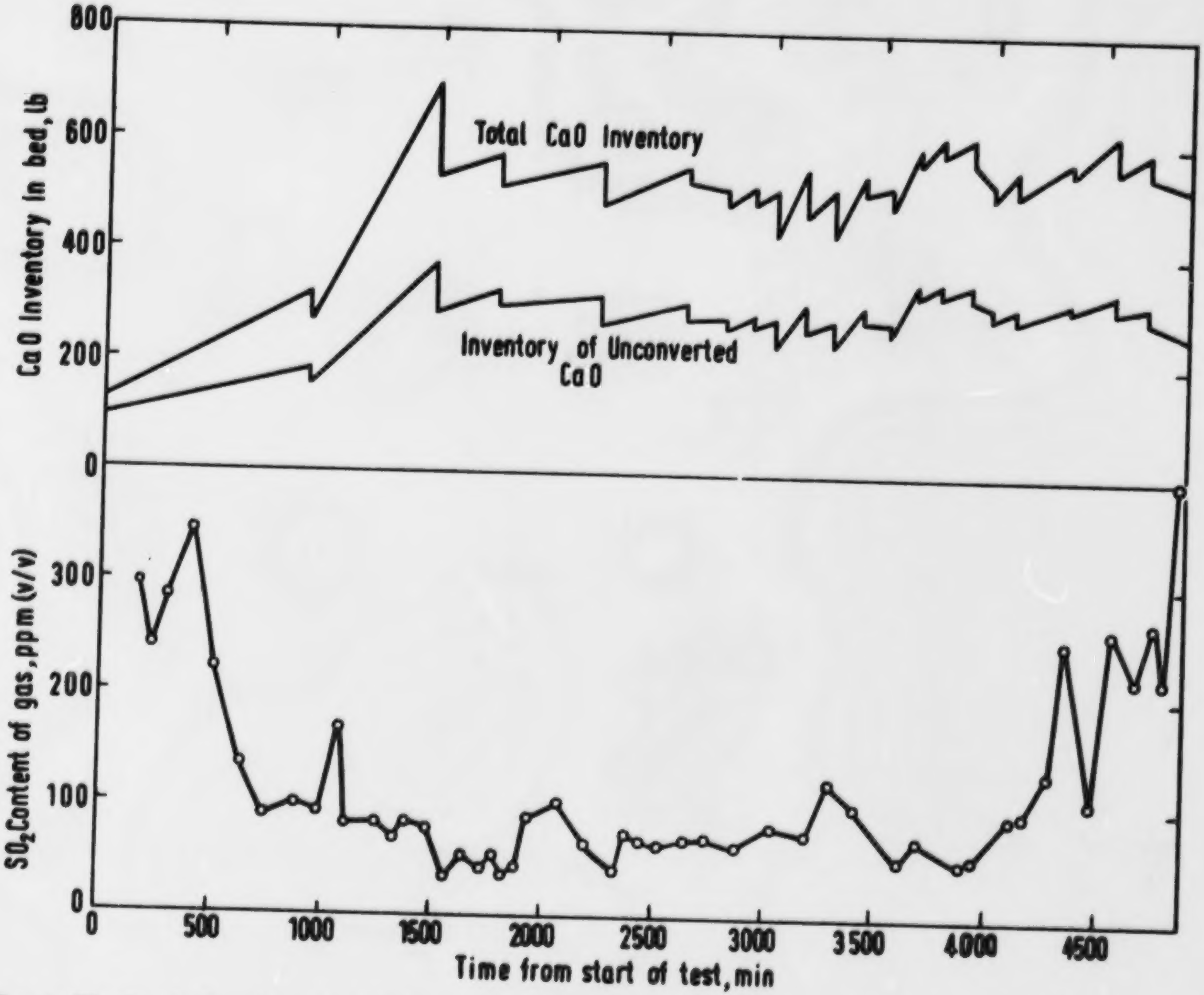
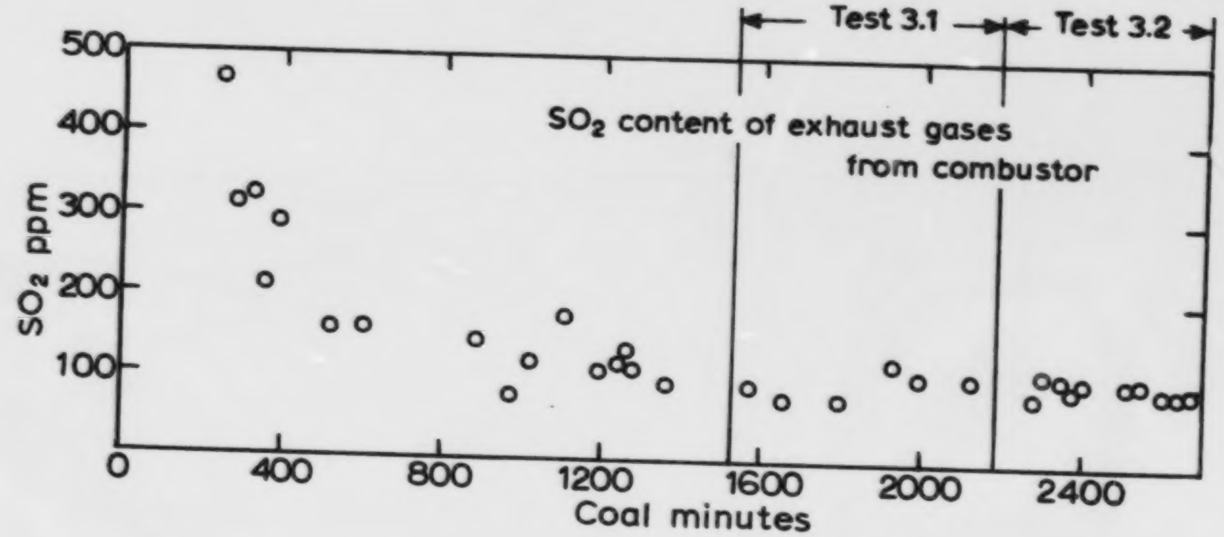


Fig.A2.3.5.Task II. Test Series 2. Variation of calcium content (total and unconverted) in bed



Test	3·1	3·2
Ca/S mol ratio	1·8	2·0
Bed temperature	1482°F	1474°F
Pressure	4·97atm	4·91atm
Fluidising velocity	1·95ft/s	1·97ft/s

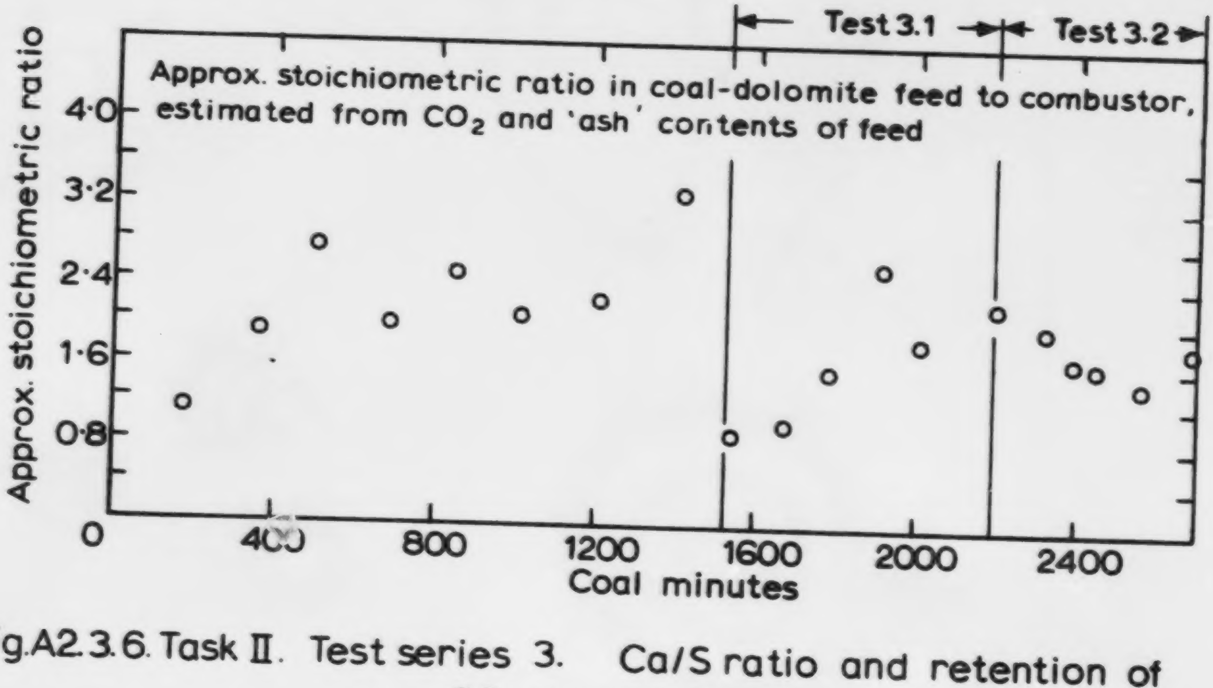
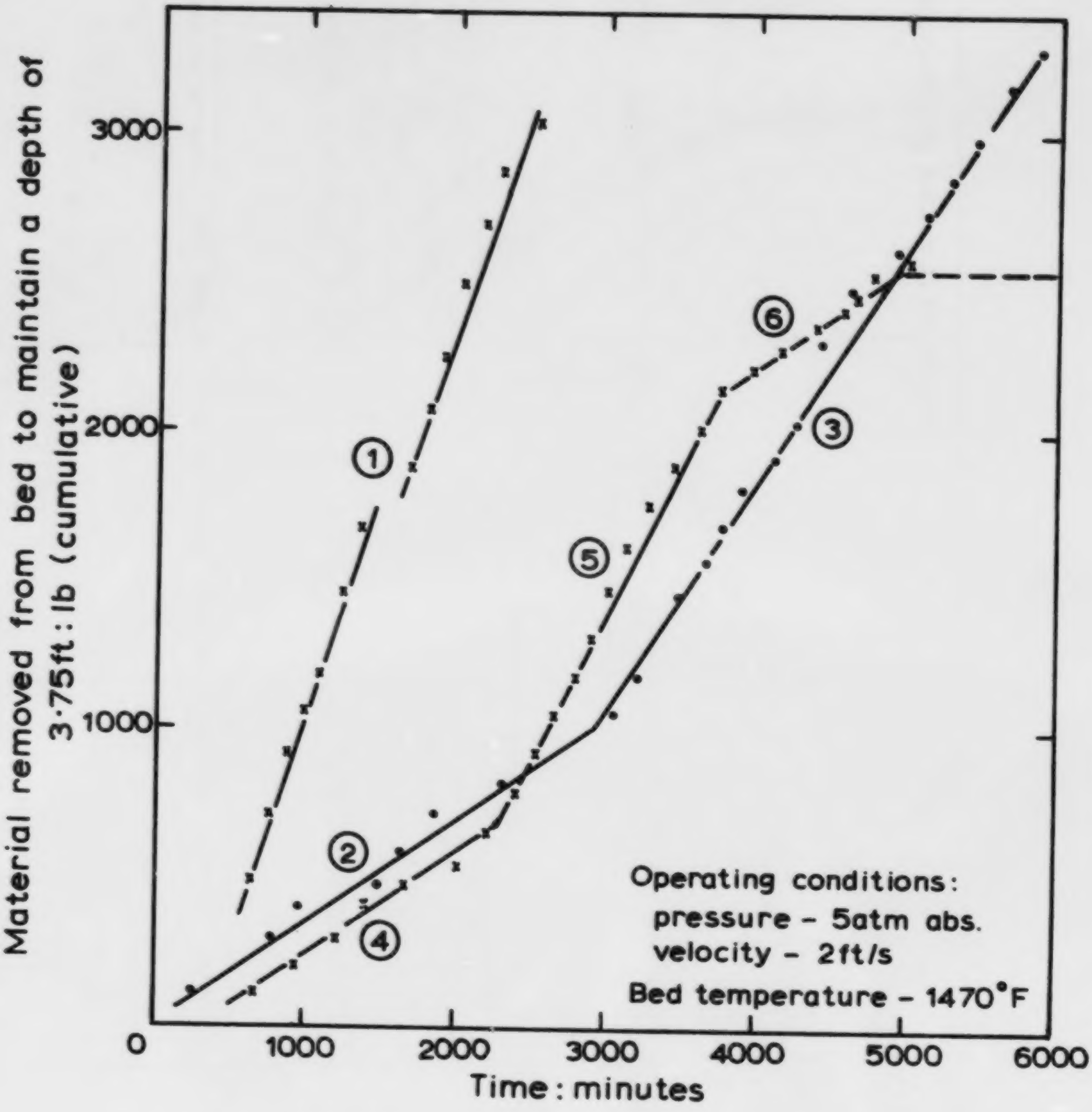


Fig.A2.3.6. Task II. Test series 3. Ca/S ratio and retention of SO_2 versus time



Operating conditions:
pressure – 5atm abs.
velocity – 2ft/s
Bed temperature – 1470°F

	Test series	Acceptor	Ca/S ratio
①	3	"Coarse" dolomite	1·8 – 2·0
②	4	"Fine" dolomite	1·7
③	"	"	2·2
④	5	Limestone	2·0
⑤	"	"	2·5
⑥	"	"Fine" dolomite	1·2

Fig. A2. 3.7.

Task II. Test Series 3, 4, 5; rate of removal of material from bed

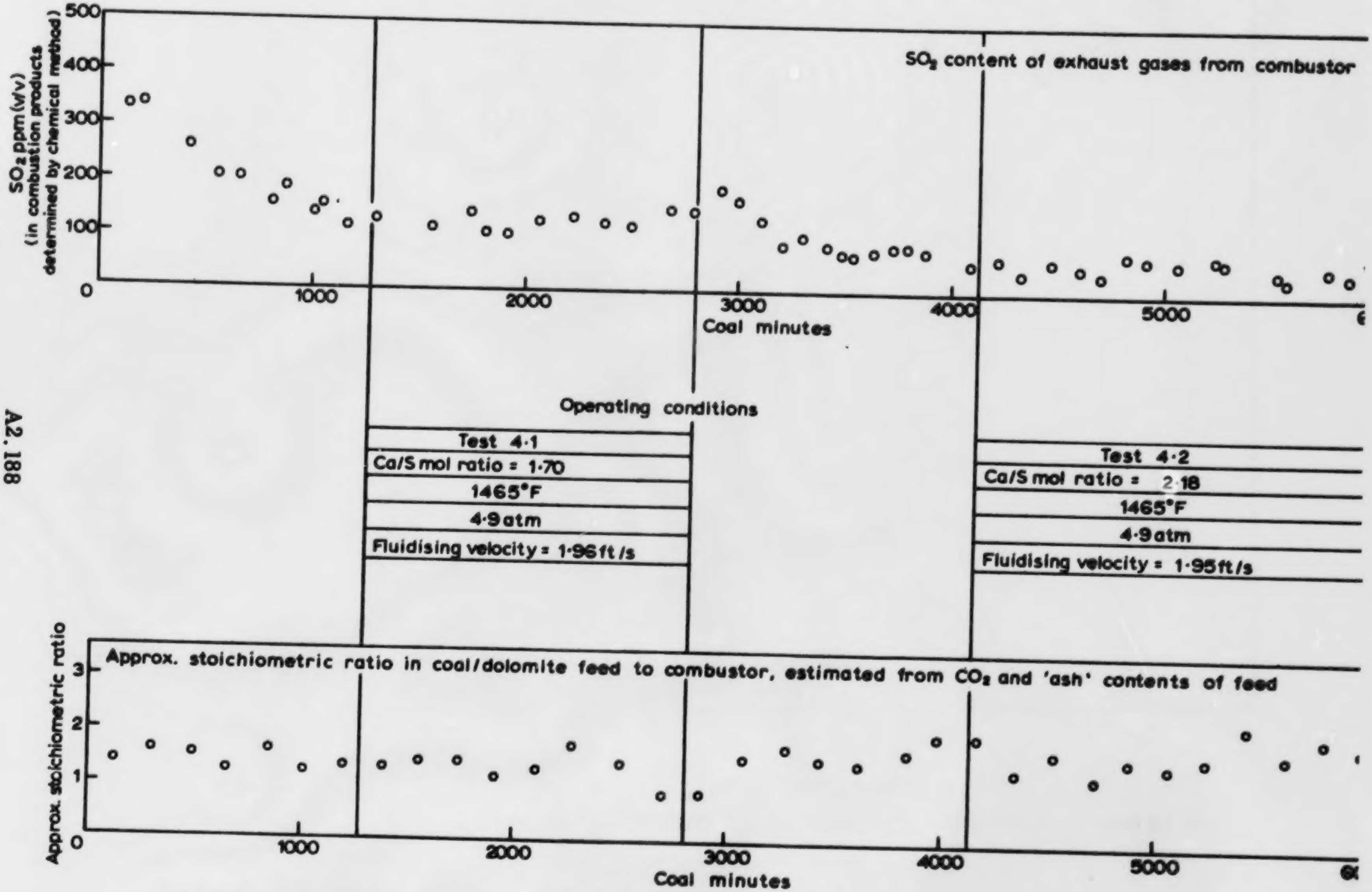


Fig. A2.3.8. Task II. Test Series 4. Ca/S ratio and retention of SO_2 versus time

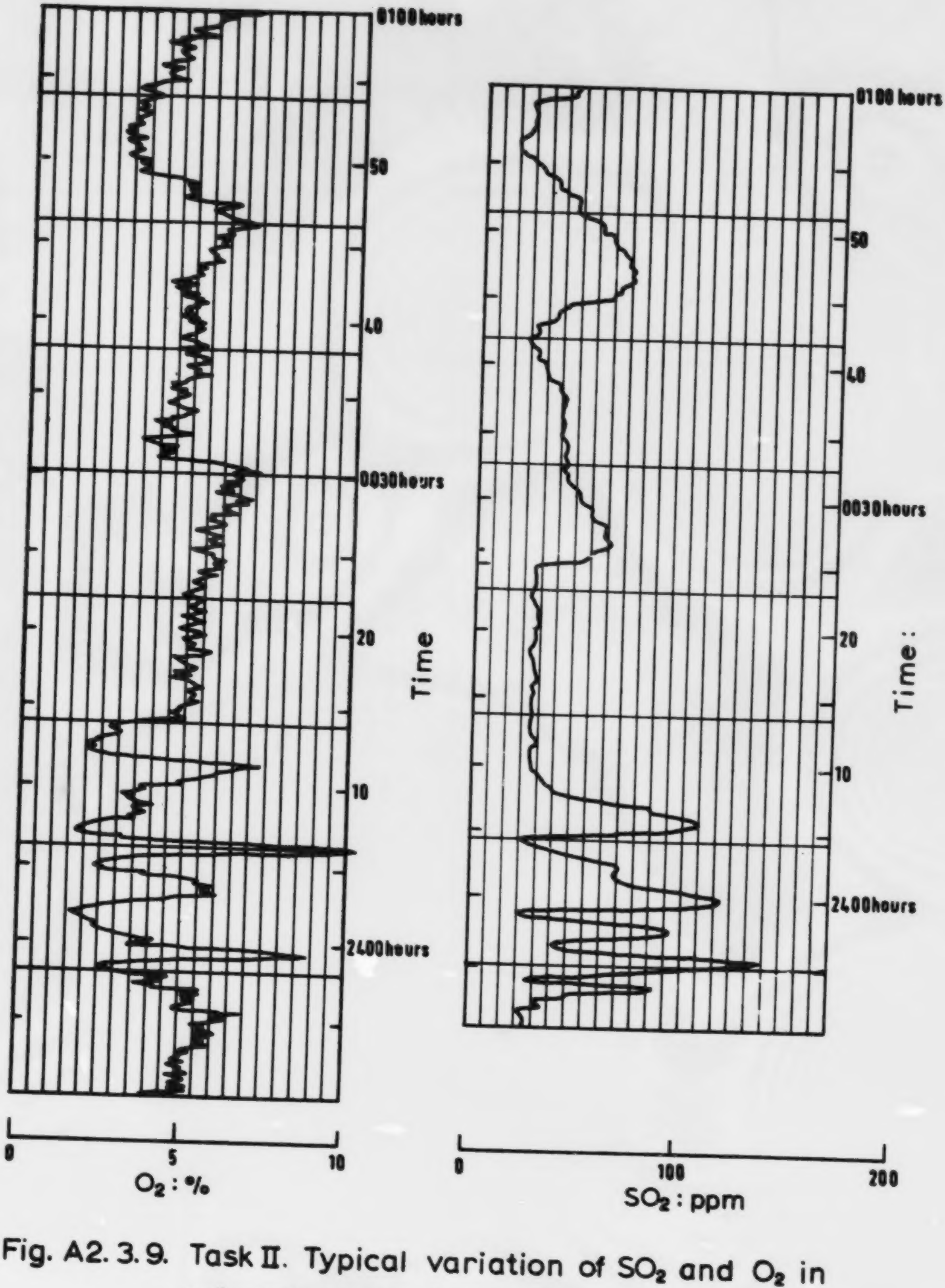


Fig. A2. 3. 9. Task II. Typical variation of SO_2 and O_2 in exhaust gases during Test Series 4

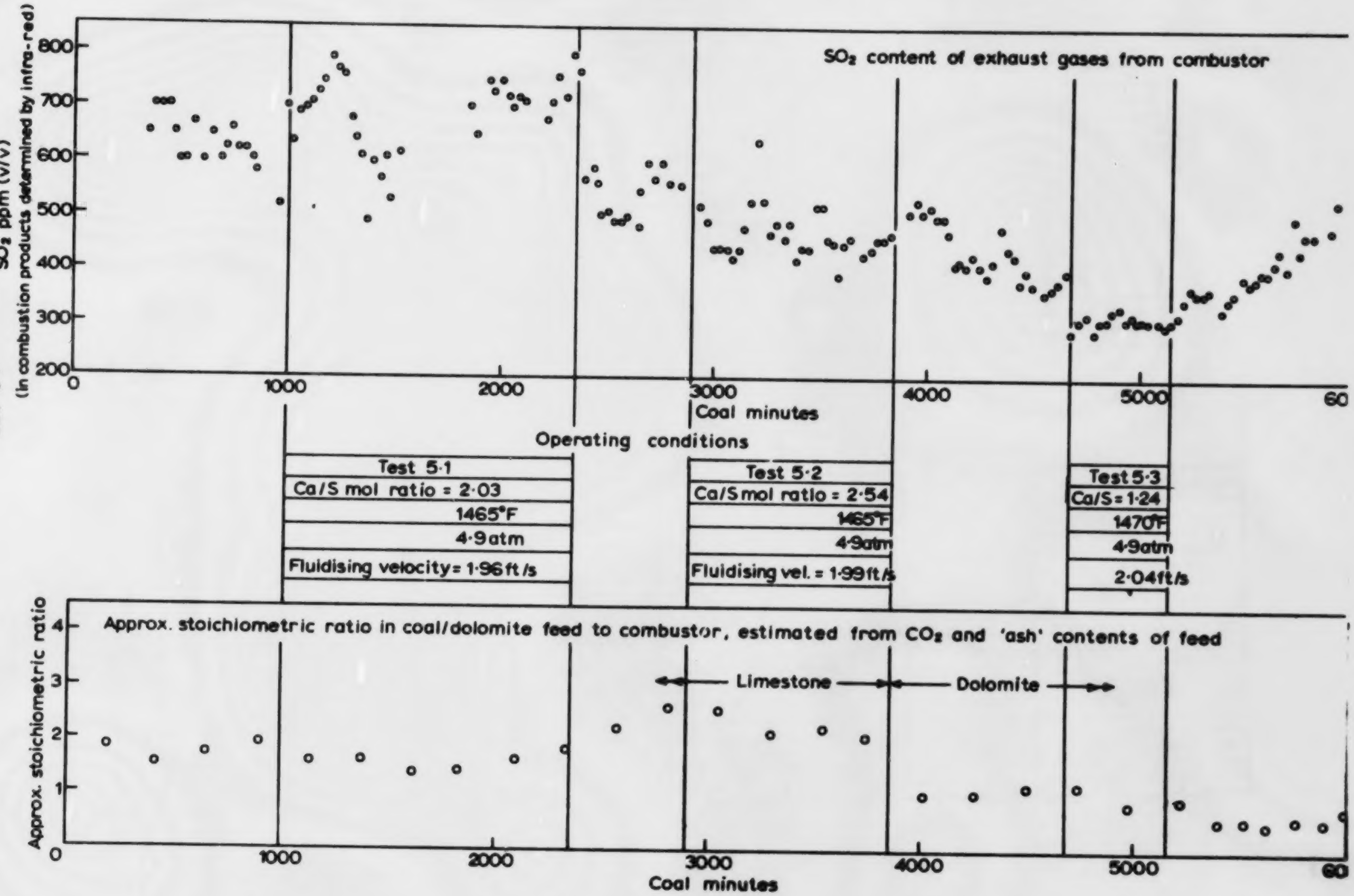


Fig. A2.3.10. Task II. Test Series 5. Ca/S ratio and retention of SO₂ versus time

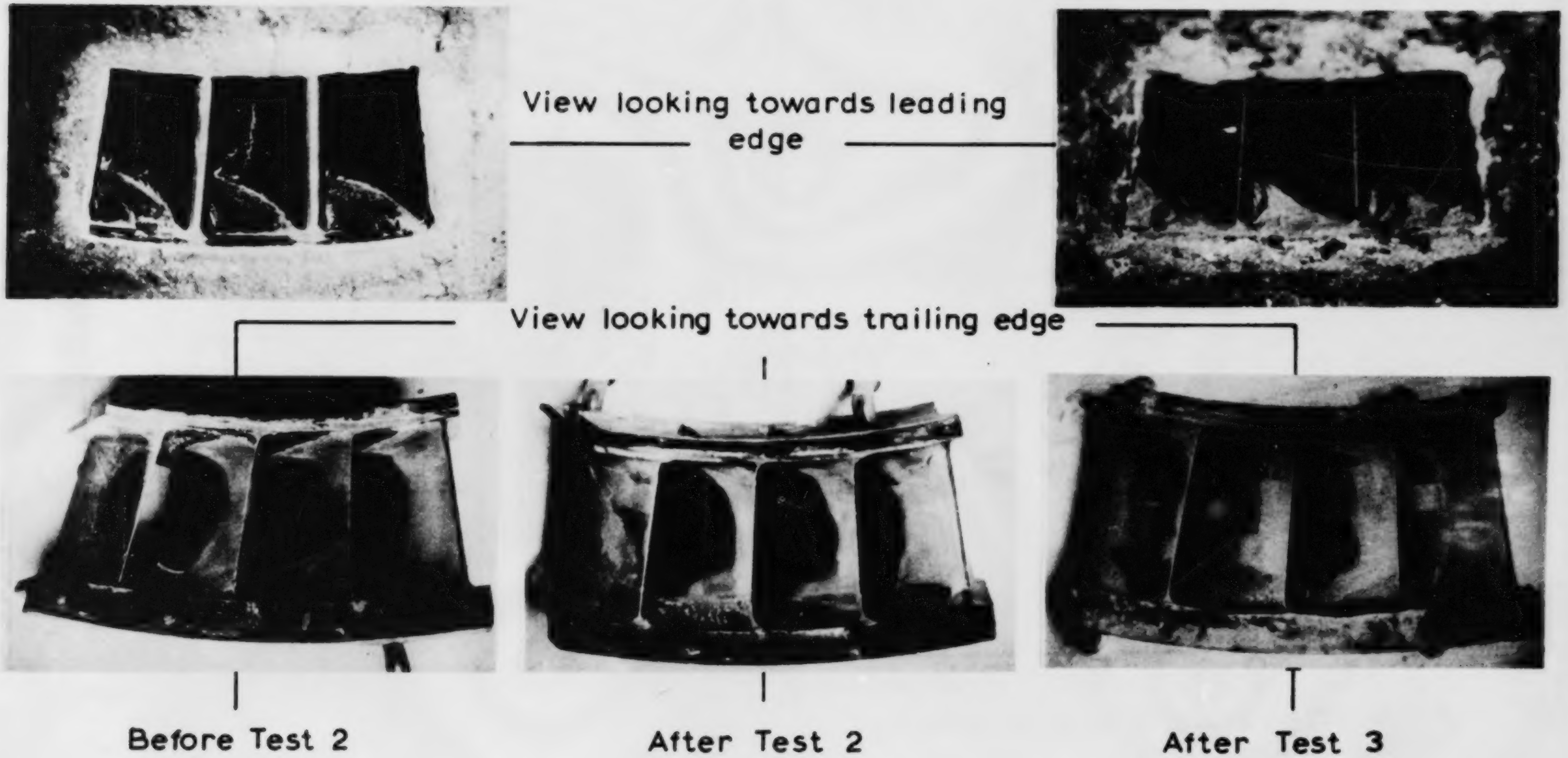
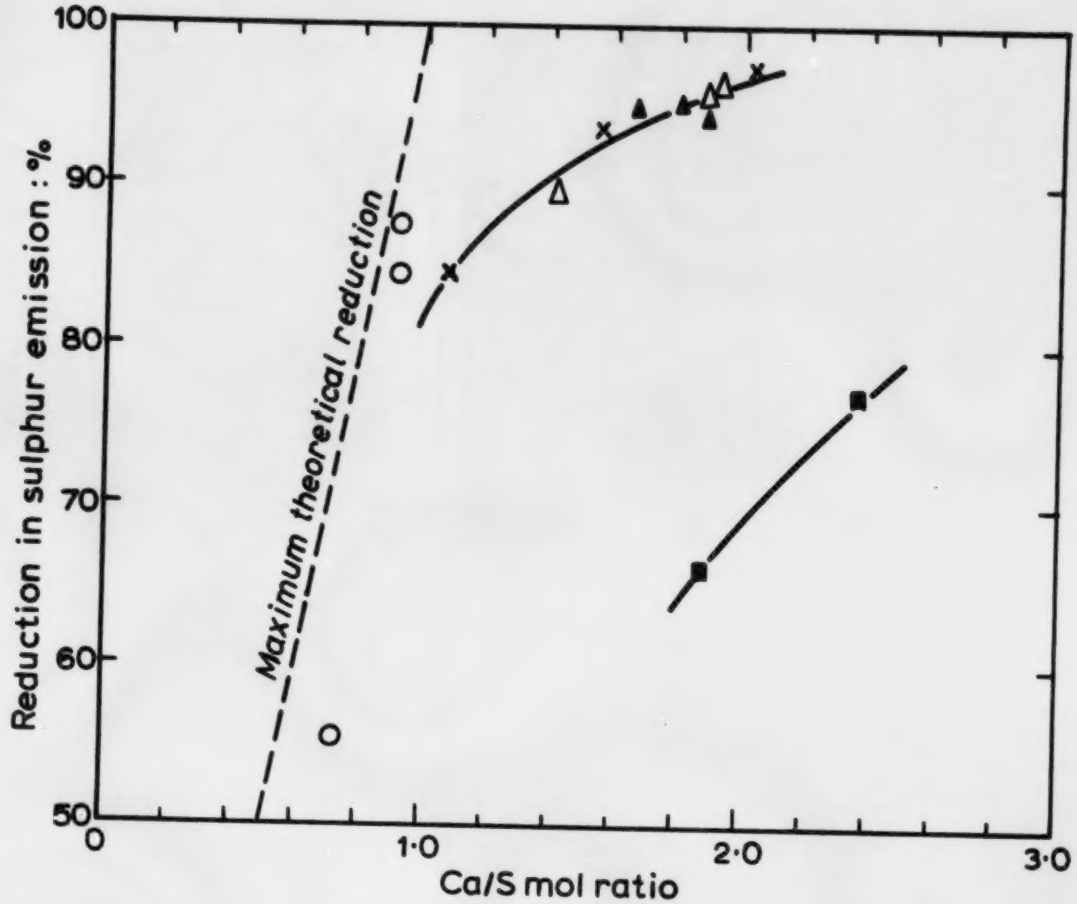

View looking towards leading edge
View looking towards trailing edge
Before Test 2
After Test 2
After Test 3

Fig.A2.3.11. Task II. Test Series 2 and 3. Appearance of blade cascade before and after tests



Fluidising velocity : c 2ft/s
Bed depth : 3·75ft
Bed temperature : c1470°F

Coal	Acceptor		Pressure : atm. abs.	
	Type	Median size: micron	$3\frac{1}{2}$	5
Welbeck	U.K. Dolomite	750	○	
Pittsburg	Dolomite 1337	1100	△	▲
Pittsburg	Dolomite 1337	400		×
Pittsburg	Limestone 18	270		■

Fig.A2.3.12. Task II. Reduction in sulphur emission

NATIONAL COAL BOARD

FINAL REPORT

JUNE 1970 - JUNE 1971

REDUCTION OF ATMOSPHERIC POLLUTION

APPENDIX 3. EXPERIMENTS WITH THE 27 IN COMBUSTOR. (TASK III)

PREPARED FOR

ENVIRONMENTAL PROTECTION AGENCY
OFFICE OF AIR PROGRAMS
411 WEST CHAPEL HILL STREET
DURHAM, NORTH CAROLINA 27701

REFERENCE NO. DHB 060971

SEPTEMBER 1971

FLUIDISED COMBUSTION CONTROL GROUP

NATIONAL COAL BOARD
LONDON, ENGLAND

A3.i

REDUCTION OF ATMOSPHERIC POLLUTION

Research on reducing emission of sulphur oxides, nitrogen oxides and particulates by using fluidised bed combustion of coal

Appendix 3. Experiments with the 27 in combustor. (Task III)

Main objective

To carry out long-term tests to assess the effect of limestone addition on corrosion of evaporator, superheater and reheater metals immersed in the fluid bed.

Report prepared by: D.M. Wilkins

Report approved by: A.D. Dainton and
H.R. Hoy

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Foreword

This Appendix describes experimental work carried out using the 27 in combustor at BCURA between June 1970 and June 1971, as Task III of the joint N.C.B./O.A.P. research programme. The objective of Task III was to carry out long-term tests to assess the effect of limestone addition on the corrosion of evaporator, superheater and reheater metals. The contract programme provided for only a narrow range of operating conditions, but it was subsequently agreed that a rather wider range of operating conditions should be explored. A summary of the work is presented in the main report and the results are discussed there, together with results from other pilot plants.

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  3.4.4 Nitrogen oxide emission A3.20

4. Acknowledgements A3.20

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Figures A3.1 - A3.11

(Note that when referring to Tables and Figures in the text the prefix A3 is omitted)

1. DESCRIPTION OF THE 27 in COMBUSTOR PLANT

1.1 The Combustor

A flow diagram of the 27 in combustor plant is shown in Fig. 1 and a section through the combustor in Fig. 2. The cylindrical section containing the fluid-bed was 27 in diameter and the shaft above this section diverged to 46 in diameter for the lower 2 ft of the freeboard before returning to a cylindrical section 24 in diameter. The height of the bed zone was 2 ft and the total height of the freeboard was 11 ft. The walls of the bed zone and freeboard consisted of twenty water-cooled jackets. Combustion products leaving the freeboard passed into a vertical water-cooled heat exchanger before entering the external dust cleaning cyclone.

The bed was supported on a bubble cap distributor plate, air for combustion being supplied via a plenum chamber located directly below the distributor plate. Crushed coal and acceptor were metered into a hopper, transported pneumatically to the combustor and injected into the fluid-bed via a horizontal 'Y' feeder. The two 1 in diameter arms of the 'Y' formed injection points which were radially equidistant from the axis of the combustor at a distance apart of 0.3 ft approximately.

A 'mushroom' gasburner fitted in the centre of the distributor plate supplied towns gas for start up. During normal operation it was used to distribute externally recycled fines.

A low efficiency cyclone positioned in the freeboard recycled +50 micron particles to the bed via a dip-leg and lock-hopper system, whilst a high efficiency cyclone external to the combustor removed solids greater than 10 micron from the combustion products. A controlled portion of the fines collected by the external cyclone could be recycled pneumatically to the bed via the 'mushroom' burner and the remainder was discharged to collection drums.

Access ports for corrosion tube assemblies and other probes were provided in the walls of the bed section.

The 2 in diameter corrosion tube assemblies were arranged at 5 in centres horizontally and 6½ in centres vertically: the dipleg from the internal cyclone prevented the use of intermediate tubes to form a triangular pattern.

A section through a corrosion probe is shown in Fig. 3. During the present series of experiments the probes were cooled with either steam or air.

1.2 Coal and Acceptor preparation and feeding

Metered quantities of coal and acceptor were mixed before being fed pneumatically to the combustor via a single injection nozzle.

The coal preparation system consisted of a storage hopper, loaded with coal from the shipping cartons and fitted with a variable speed rotary valve which discharged coal via an inclined screw conveyor to a gyratory separator fitted with a 3175 micron mesh screen. Oversize coal from the screen was fed to a hammer mill, the crushed product being returned to the separator. Undersize coal from the screen was transported by a bucket elevator and a conveyor belt to an 8 ton prepared coal storage hopper (Fig. 1). Prepared coal was metered from the storage hopper by a pneumatically operated weighing conveyor and discharged into a small transfer hopper.

Acceptor material, sized according to the particular test requirements, was dried on a steam-heated drying floor before use. The dried acceptor was loaded into the feed hopper by a skip capable of holding up to one hour's supply at the highest feed rate. A 4 in diameter screw at the base of the feed hopper was driven by a variable speed motor and metered the acceptor into the stream of coal falling from the weighing conveyor into the transfer hopper (Fig. 1).

The coal-acceptor mixture was transferred by a constant speed rotary valve fitted to the base of the transfer hopper into a 1¼ in n.b. pipe and conveyed pneumatically to the combustor.

Prior to test series in which coarse (-3175 micron) limestone was to be used, a sufficient amount of limestone from the shipping cartons was crushed in the same system as used during the tests to prepare coal to -⅛ in, and stock-piled until required. Fine (-150 micron) limestone was prepared by an external contractor by drying and crushing the raw granular limestone. Dolomite from the shipping cartons was broken in a jaw crusher, screened on a gyratory separator fitted with a -1587 micron mesh screen and the undersize fraction stockpiled until required for testing.

1.3 Instrumentation

Combustion air and air supplies for coal and grit transport were metered by orifice assemblies fitted with differential pressure transducers for remote flow indication.

Static pressures in the plenum chamber below the distributor plate, in the freeboard and at the combustor exit were indicated on panel-type gauges. The differential pressure between the plenum chamber and the freeboard was used to compute the weight of material in the bed.

Bed temperatures were measured at 3, 9, 15 and 21 inches above the distributor plate level and a suction thermocouple was used to measure exit gas temperature.

A small flow of gas was continually drawn from the top of the combustor through a stainless steel gas sampling probe by a small diaphragm pump. The gases were passed through a glass wool filter, a water trap and three silica gel dryers in series, before being supplied to a paramagnetic oxygen analyzer and infra-red CO_2 and CO analyzers. Cylinders of known composition were periodically used to calibrate the analyzers. Sample gas for the determination of SO_2 by the iodine and Hartman-Braun infra-red methods, and also for the determination of NO_x by the Saltzman method was obtained from a similar system which sampled gases from the 12 inch diameter duct between cyclone exit and the I.D. fan.

Estimates of the concentration of dust in the 12 in diameter duct between the external cyclone and the I.D. fan were made by isokinetic sampling of the gas stream through a probe of accurately known bore and collecting the dust over a 10 minute period in the standard BCURA high efficiency dust sampling cyclones.

The instrumentation included warning bells for low steam pressure and low air pressure in the pneumatic transport and corrosion probe cooling systems.

The weights of material removed from the bed and of fines removed from the external cyclone were obtained by direct weighing

1.4 Corrosion Probes

The general assembly of the corrosion probes is illustrated in Fig. 3. The section of the probes exposed to the combustor bed comprised 26 metal rings all lapped and spigotted together to form a continuous tube. These rings were machined from medium carbon, ferritic and austenitic steel bars or tubes to the shape shown in Fig. 4. Twenty three of the rings were test specimens for assessing corrosion rates whilst the remaining three rings each held three 1/16 in o.d. chromel-alumel thermocouples for measuring metal temperatures. The arrangement of the thermocouples is shown in Fig. 4: they entered the probe through glands in the inlet manifold, passed along the annulus between the bore of the rings and the centre tube and terminated in a tight push fit in drilled holes in the ring. Access to these locating holes was provided by machining grooves in the preceding specimen ring. In order to maintain the metal temperatures at the required level, one thermocouple from each probe was connected to a Honeywell proportional controller operating a motorised valve in the steam (or air) supply to the probe. The remaining eight thermocouples in each probe were used for record purposes.

In Test Series 1 and 2 (500 hours and 1000 hours), the corrosion specimens were cooled with steam at approximately 30 psig, flow being controlled by the Honeywell motorised valves.

The two lower probe assemblies were controlled at 750°F and 930°F, and the upper assemblies to 1110°F and 1230°F. During Test Series 1, waste steam from the probes was piped to an external cooler and then to waste, whilst during the remaining tests the steam was vented to atmosphere.

In Test Series 3 only two corrosion probes were installed in the bed, these being nominally at 750°F and 930°F. They were cooled by compressed air as the steam in Test Series 1 and 2 was found to corrode the inside of some of the less resistant steels. Steam lines were still connected into the system however, so that in an emergency the corrosion probes could be supplied with steam. Bed cooling tubes were installed in place of the nominal 1110°F and 1290°F corrosion probes and supplied with steam. The motorised valves were operated by Honeywell proportioning controllers, to adjust the steam flow to match changes in the bed temperature, measured 9 in above the distributor.

In Test Series 4, corrosion probes were excluded altogether, as it was agreed that 100 hours operation was too short a period for obtaining reliable data on the corrosion of low alloy steels; consequently only the two steam-cooled bed tubes were retained.

1.5 Data processing

(i) Weights and flow rates

Coal and Acceptor: The individual flow rates were obtained from the operational settings and calibrations of the two feeders.

Air: Total air supplied for combustion was the sum of the air flow through the distributor, plus the coal and grit recycle conveying air flows.

Bed extract: The flow-rate of bed extract was the actual weight of bed material removed during a control period divided by the duration of the control period in hours.

Cyclone fines: The flow-rate of cyclone fines was the actual weight of solids removed from the external cyclone during a control period divided by the duration of the control period in hours.

Exhaust dust: The flow-rate of dust escaping from the external cyclone was assessed by multiplying the flow-rate of dust collected by the sample probe under iso-kinetic conditions, by the ratio of cross-sectional area of duct to the cross-sectional area of the probe.

Flue Gas: The flow-rate of dry flue gas was calculated knowing the solids and air inputs to the plant, the gas composition of the combustion products and assuming a nitrogen balance. The water vapour content of the combustion products was calculated assuming a hydrogen balance.

(ii) Operating parameters

The following parameters were calculated for each test:

$$\text{Excess air level} = \frac{\text{Feed air - Stoichiometric air for coal feed}}{\text{Stoichiometric air for coal feed}} \times 100\%$$

$$\text{Unburnt Carbon} = \frac{\text{Carbon in bed extract, cyclone fines and dust}}{\text{Carbon input}} \times 100\%$$

$$\text{Ca/S mol ratio} = \frac{\text{mols of Ca in additive}}{\text{mols of S in coal}}$$

$$\text{Sulphur retention} = 1 - \frac{\text{Sulphur in flue gas}}{\text{Sulphur in coal}} \times 100\%$$

$$SO_2 \text{ reduction} = \frac{(SO_2)_d - (SO_2)_a}{(SO_2)_d} \times 100\%$$

where $(SO_2)_d$ is the emission in a datum test without additive

and $(SO_2)_a$ is the emission with additive

(iii) Mass balances

Mass balances were carried out for the following materials in a few typical tests.

Ash: Ash content of coal was determined by the normal analytical method. Ash content of acceptor was assumed to be $(100-\%CO_2)\%$. "Ash" content of output solids was assumed to be $(100-\%SO_3-\%$ combustible$)\%$.

Combustible: The combustible in bed extract and exhaust dust was assumed to be carbon. The combustible in cyclone fines was assumed to be carbon and sulphur from the coal. The sulphur was assumed present as sulphide and the sulphur/carbon ratio was assumed to be half of that in the coal.

Hydrogen: No hydrogen or methane was detected in the combustion products, hence the total hydrogen input was assumed to be converted to water vapour.

Nitrogen: For the purposes of the mass balances, nitrogen oxides (NO_x) in the combustion products were assumed present as nitric oxide. The elemental nitrogen in the combustion products was obtained by difference and thus includes analytical errors.

Oxygen: The oxygen content of the coal was obtained by difference and therefore includes analytical errors. The oxygen contents of bed extract, cyclone fines and exhaust dust were assumed to be present in sulphate. Oxygen from carbon dioxide content of input and output solids has not been included in the oxygen balance.

Sulphur: Half of the sulphur in the coal was assumed present as sulphate and the remainder as sulphide. Sulphur in bed extract and exhaust dust was assumed to be present as sulphate. Sulphur in cyclone fines other than that associated with the combustible (see above) is assumed present as sulphate.

Calcium and Magnesium: These elements were determined in the input and output solids as oxides. The oxygen combined with them was not included in the oxygen balance.

2. OPERATING PROCEDURES

2.1 Start-up

The bed was preheated by burning a mixture of 70 lb/h towns gas and 130 lb/h air at the gas burner at the base of the bed whilst fluidising the bed with combustion air. When the temperature of the bed reached 650°F, 40 lb/h coal was introduced into the bed via the coal nozzle. This resulted in a rapid increase in bed temperature. Coal feed and combustion air rates were progressively increased until the required test conditions were attained. At a bed temperature of 1470°F, the towns gas supply was discontinued and recycle of grit from the external cyclone commenced.

2.2 Establishment of Equilibrium

Test Series 1 was run at constant operating conditions throughout, whereas Test Series 2 and 3 consisted of a number of shorter term tests, conditions being changed approximately every 60 hours. The final 16 hours at each set condition comprised the actual test period during which samples were taken and rates of removing bed material and cyclone fines from the plant were measured accurately. Thus a period of approximately 44 hours was allowed in which equilibrium could be established.

During these tests it was found that providing no change in the composition of acceptor material was made, equilibrium values of SO_2 were attained in 4 to 6 hours after changing operating conditions. When acceptor composition was changed, a longer period, about 10 hours, was needed before the SO_2 concentration in the exit gases became steady. In Test Series 4, which was run solely to extend the data on effect of operating conditions on SO_2 emission, 9 short tests were carried out. In general, a six hour period was allowed for conditions to attain equilibrium prior to a control test of 4 hours duration. The exceptions were the 22 hour period between start-up and commencement of the first test and the 10 hour settling period allowed between the end of test 4.1 and start of test 4.2 because acceptor was changed from limestone to dolomite.

2.3 Sampling Procedures

During each of the test series, coal was sampled from a point between the main storage hopper and the coal weigher once every eight hours, and the accumulated bulk sample obtained after each hundred hour period was analysed. At the end of each test series a bulk sample containing part of each of the 100 h samples was sent for a more complete analysis.

During the control tests of Test Series 2, 3 and 4, bed extract and cyclone fines were sampled as the appropriate dumping bins required changing, a bulk sample of each material being accumulated over the period of the control test. These products were then analysed for size distribution, carbon, CaO, MgO and SO_3 content.

Dust carried over in the flue gases was sampled at a point in the exit duct after it has passed through the external cyclone. Two samples were taken during each control test and mixed to give one bulk sample. The samples were then analysed for carbon, CaO, MgO, and SO_3 content and size distribution by Coulter counter.

A continuous sample of flue gases was drawn from the exit of the combustor using a simple probe and diaphragm pump and analysed for CO_2 and CO by infra-red analysers. A paramagnetic type analyser was used to measure O_2 concentration. Spot samples were also taken during control tests via a simple probe situated in the exit duct and analysed by conventional chemical methods for SO_2 and NO_x. The SO_2 was determined by the standard iodine/thiosulphate titration and the NO_x using Saltzman's reagent. In addition, gas from this probe was fed continuously to an infra-red SO_2 analyser.

2.4 Shut-down Procedure

The coal weigher, limestone feeder and the grit valve were switched off simultaneously, leaving the coal valve, coal feed air and grit feed air supplies open to clear the respective feed lines completely. The coal valve was then shut-off. When the bed temperature fell below the controlling temperature of the steam-cooled corrosion probes, the steam supply was shut off. As the bed temperature dropped to $400^{\circ}F$ the cooling water supply to jackets and probes was turned off to prevent condensation inside the combustor. When the bed temperature dropped to below $212^{\circ}F$ the I.D. and then the F.D. fans were switched off.

2.5 Emergency Procedures

The normal supply pressure of the combustion air was 80 p.s.i.g. A warning bell operated if the supply pressure fell below 75 p.s.i.g.; this gave adequate time for a stand-by compressor to be started up.

For Test Series 2, compressed air was available to replace the steam supply for cooling the corrosion probes in the event of failure of the boiler. For Test Series 3, in which the corrosion probes were air-cooled, steam was available as the stand-by coolant in the event of a failure of the air compressor.

3. RESULTS

3.1 Test Series 1

3.1.1 Objectives of the Test Series

(i) To measure the corrosion rate of specimens of boiler steels immersed in the fluid-bed for 500 hours without addition of limestone.

(ii) To measure the rate of sulphur emission from the plant when burning Pittburgh coal.

3.1.2 Description of Test Series 1

The first attempt to carry out this test series, designated Test 1a, had to be abandoned when the steam supply to the corrosion specimens failed after 147 hours of operation. The 500 hour run designated Test 1b was successfully carried out from 16th November to 7th December, 1970.

Operating conditions are given in Table 1 and analyses of coal, bed extract, cyclone fines and exhaust dust samples collected during test series 1b are given in Tables 2 to 6. Average gas composition data for sequential 100 hour periods together with temperatures in the bed at four heights above the distributor plate are given in Table 7. An overall summary of the rates of bed extraction, cyclone fines and dust in the stack gases is given in Table 8.

3.1.3 Sulphur Emission

Between two and four measurements of sulphur dioxide content of the combustion products were made every third day of the test series using the iodine absorption method. In all, six determinations were made during Test Series 1a and 23 determinations during Test Series 1b: the 29 values are reported in Table 9. The means and variances of the two sets of measurements were not significantly different; based on a 95% level of probability the mean value of all the determinations was 2053 ± 36 ppm SO_2 v/v. The 95% confidence limits on a single determination were ± 190 ppm SO_2. This level of sulphur dioxide emission corresponds to a sulphur retention in the bed of 21% and is in accord with the calcium in the ash having reacted completely with sulphur from the coal.

3.1.4 Corrosion of Metal Specimens

There were four corrosion probes at nominal temperatures of 750°F, 930°F, 1110°F, 1290°F; all were cooled with steam from the central heating boiler. Some difficulty in controlling probe temperatures was initially experienced due to water condensing in the steam lines. This was minimised by lagging the pipes. Figure 5 shows the close control over outlet temperature that was achieved after eliminating the condensation effects.

The specimens from test series 1b were examined visually for deposits and corrosion or erosion damage. The majority of the test specimens were then descaled by immersion for five minutes in a bath of molten sodium hydroxide containing 2% sodium hydride maintained at 680° to 715°F. The weights of the descaled specimens were then subtracted from their weights before exposure in the fluid-bed combustor during the test series. The resulting estimates of rate of corrosion during test series 1b are given in Table 10. The low chromium and mild steel specimens were found to have suffered some internal corrosion, probably as a result of condensate being carried forward into the probes and to the use of steam obtained from untreated water. The internal profiles of these specimens were accurately identified using a Talysurf profilometer and the necessary corrections were applied to the weight losses of the specimens before computing the corrosion rates of these steels.

3.2 Test Series 2

3.2.1 Objectives of the Test Series

(i) the rate of corrosion of boiler steels in a fluid-bed in the presence of limestone.

(ii) the sulphur retention at different levels of Ca/S mol ratio when burning Pittsburgh coal in the presence of Limestone 18.

(iii) the effect of limestone particle size on sulphur retention,

and (iv) the effect of bed height on sulphur retention (with zero recycle of cyclone fines).

3.2.2 Description of Test Series 2

Test Series 2 was run continuously for a 1000 hour period from 19th January to 2nd March 1971. Fluidising velocity, coal input rate and bed temperature were maintained nominally constant throughout the test series at 8 ft/s, 230 lb/h and 1550°F, respectively. Eighteen tests were carried out using two sizes of limestone over a range of feed rates and with and without fines recycle. Details of the operating conditions in each test are given in Fig. 6 and Table 11.

The first three tests, 2.1, 2.2 and 2.3, were carried out with coarse (-3175µm) limestone with fines recycle from the external cyclone in addition to internal recycle. The next five tests, 2.4 to 2.8 were with fine(-150µm) limestone, again with external fines recycle. The following two tests, 2.9.1 and 2.9.2 were carried out to assess the effect of bed height with fine limestone but without external recycle. It was necessary to compensate for the lower combustion efficiency without recycle by increasing the coal feed rate slightly.

After carrying out a datum test with fines recycle but without additive (Test 2.10) a further series of tests was carried out with coarse limestone and recycle, (Tests 2.11 to 2.15). Finally two tests, 2.16.1 and 2.16.2, were carried out with coarse limestone but without recycle for comparison with tests 2.9.1 and 2.9.2.

The 1000 hours operation was completed at 1400 hours on 2nd March 1971.

The four corrosion probes immersed in the fluid bed were cooled by steam to nominal metal temperatures of 750°, 930°, 1110°, and 1290°F.

Chemical analyses and size gradings of coal, limestone, bed extract, cyclone fines and exhaust dust for each of the tests comprising Test Series 2 are given in Tables 12 to 16. A more detailed coal analysis is given in Table 3 for the bulk sample collected for the test series.

Average gas composition data, together with temperatures in the fluid bed at four heights above the distributor plate are tabulated in Table 17. Table 18 summarises the mass flow-rates of air, coal and acceptor fed to the combustor and the flow-rates of bed material, cyclone fines and exhaust dust removed from the plant.

3.2.3 Sulphur emission

Two methods of assessing the sulphur dioxide content of the exit gases were used during Test Series 2, viz. the Hartmann Braun infra-red gas analyser and the chemical method used in Test Series 1. Good agreement between the methods was obtained; the values used for calculation purposes were obtained by the chemical method.

Mean sulphur dioxide concentrations in the exit gases are reported in Table 19, together with salient operating details and sulphur retention by the bed material. This data has been plotted in Fig. 7 to show the effect of Ca/S mol ratio and limestone particle size on sulphur retention and SO_2 reduction. The value obtained from Test Series 1, at zero limestone input, has been included in the plot. At a bed temperature of about 1550°F and a fluidising velocity of 8 ft/s coarse limestone (-3175 micron) was more effective in 'fixing' sulphur than the fine (-150 micron) limestone. Presumably the increase in available surface offered by the fine limestone does not offset its shorter residence time in the fluid-bed. For both size grades, utilisation of the calcium oxide from the limestone decreases with increasing limestone addition.

As shown in Table 19A, Test Series 2 affords:

(i) 4 replicate estimates of SO_2 reduction.

(ii) 2 comparisons of the effect of weight of solids in the fluid-bed on SO_2 reduction without external recycle.

(iii) 1 comparison of the effect of bed temperature on SO_2 reduction when coarse limestone was added to the bed.

In this table, (19A), sulphur dioxide concentrations in the combustion products, and hence SO_2 reduction, have been corrected to zero excess air conditions.

It is concluded that when the coarse or fine grades of limestone were added to the bed, increasing bed weight by about 30% did not result in an increase in the SO_2 reduction.

3.2.4 Nitrogen oxide emission

The nitrogen oxides concentration in the combustion products was determined by the Saltzman method (see Appendix 9). Individual results are tabulated in Table 20 and mean values for some of the tests are given in table 17.

Operating conditions in Tests 2.5 and 2.7 were essentially identical, as were those in Tests 2.6 and 2.8. The mean NO_x concentrations in these duplicate tests, in which fine limestone was added, were not significantly different, suggesting that increasing the Ca/S mol ratio from 1.18 to 3.55 has no effect on NO_x emission. These mean concentrations were also not significantly different from the mean value for Test 2.1 in which coarse limestone was added to the bed to give a Ca/S mol ratio of 2.25. Pooling all these results leads to a mean value of 434 $\pm$ 107 ppm NO_x based on 7 degrees of freedom at the 5% level of significance. This mean, however, differs significantly from the level of 297 ppm NO_x obtained during the period between Tests 2.3 and 2.4 when zero limestone was added to the bed. The gas analyses for these sections indicate that the combustion efficiency was substantially constant regardless of the changes in operating conditions.

3.2.5 Corrosion of Metal Specimens

The four corrosion tube assemblies were maintained at nominal temperatures of 750°, 930°, 1110° and 1290°F throughout Test Series 2 by cooling with steam from the central heating boiler. The procedures used to examine and assess the metal specimens were identical with those given earlier for Test Series 1b, and lead to the estimates of rate of corrosion tabulated in Table 21.

The results of a microscopic examination of a number of selected specimens are given in Table 22.

The surfaces of the high chromium steels were mainly smooth while the low alloy steels had rougher surfaces particularly when the weight losses were high.

Intergranular penetration was confined to specimens exposed at temperatures of 1110°F and above and was generally accompanied by sulphidation. In some samples, sulphide globules could be seen as a band in advance of the broadened grain boundaries. The penetration was also generally associated with some oxide formation.

3.2.6 Mass Balances

Balances have been computed for ash, carbon, oxygen, nitrogen, sulphur, calcium and magnesium for tests 2.6, 2.7, and 2.9.2. These are presented in Tables 40, 41 and 42 respectively.

3.3 Test Series 3

3.3.1 Objectives of the Test Series

(i) To measure the rate of corrosion of boiler steels.

(ii) To assess the effect on sulphur retention in the bed of:

(a) Variation in fluidising velocity at constant Ca/S mol ratio for different size gradings of limestone and dolomite, and

(b) Operating at a higher bed temperature.

3.3.2 Description of Test Series 3

Test Series 3 was run continuously for the 500 hour period from 16th March to 6th April 1971. It comprised seven tests ranging in duration from 48 h to 72 h with the terminal 16 hours in each test providing the actual test section.

Details of operating conditions are given in Fig. 8 and Table 23. Four tests, Tests 3.1 to 3.4 were carried out at fluidising velocities of 6 and 11 ft/s, with and without external recycle of fines, whilst adding limestone 18 of 3175 micron maximum particle size to the bed. In a further test, Test 3.5, -3175 micron limestone was added to the bed whilst it was fluidised at 8 ft/s and maintained at a higher temperature than usual (viz. 1660°F instead of 1560°F). The limestone feed for Test 3.6 was prepared to -150 micron. The fluidising velocity was approximately 6 ft/s and the bed temperature was maintained at the normal level of 1560°F. Hence, apart from acceptor size, Test 3.6 was a repeat of Test 3.1. The operating conditions for Test 3.7 were similar to those of Test 3.5 except Dolomite 1337 having a top size of 1587 micron was used as the acceptor.

It had been hoped that tests could have been carried out at a fluidising velocity of 4 ft/s, but fluidisation was unsatisfactory at this velocity.

In order to be able to attain higher bed temperatures during this test series, the upper two corrosion probes were removed and replaced by steam-cooled bed tubes. Steam flow through these tubes was controlled by a motorised valve operated by a Honeywell controller which sensed the bed temperature at 9 inches above the distributor plate.

Because of the need to accumulate more data on the corrosion of low alloy steels, the two remaining corrosion probes were operated at 750°F and 930°F.

Chemical analysis and size gradings of coal, bed extract, cyclone fines and exhaust dust for each of the above tests are tabulated in Tables 24 to 27. A more detailed coal analysis is given in Table 3 for the bulk sample collected during the test series. The chemical compositions and typical size gradings of the -3175 micron Limestone and -1587 micron Dolomite are given in Table 13.

Average gas composition data, together with temperatures in the fluid bed at four heights above the distributor plate are given in Table 28. Mass flow rate data for air, coal and acceptor fed to the combustor, and the flow rates for bed material, cyclone fines and exhaust dust removed from the plant are summarised in Table 29.

3.3.3 Sulphur emission

Two estimates of the sulphur dioxide concentration in the combustion products were made by the chemical method during each of the seven tests in Test Series 3. The mean values of the two estimates for each test are reported in Table 28; these have been used for calculating SO_2 reduction and sulphur retention by solid materials (Table 30). In calculating SO_2 reduction, the datum SO_2 emission without additive was assumed to be 2050 ppm SO_2 as found for Test Series 1.

Data from Table 30 have been used to plot the curves drawn in Fig. 9, to show the dependence of sulphur retention and SO_2 reduction on fluidising velocity for the -3175 micron limestone. Sulphur retention declines slightly with increasing fluidising velocity. External recycle of cyclone fines increased retention at the lower velocity of 6.4 ft/s, but not at 11 ft/s.

An estimate of the effect of fluidising velocity on sulphur retention during operation at 1560°F with fine (-150 micron) limestone can be obtained by comparing the data for Test 3.6 with the interpolated values from Fig. 7 at 2.7 Ca/S mol ratio.

	Fluidising velocity ft/s	SO_2 reduction %	Sulphur retention %
Test 3.6	6.4	83	88
Fig. 7	8.1	70	80

Hence it is concluded that with both fine and coarse limestone, operation at a lower fluidising velocity decreased sulphur emission.

An estimate of the effect of bed temperature on sulphur retention at 8 ft/s with -3175 μm limestone at a Ca/S mol ratio of 2.7 can be obtained by comparing the results from Test 3.5 with interpolated values from Fig. 7.

	Bed Temperature	SO_2 reduction, %	Sulphur retention, %
Test 3.5	1660°F	58	66
Fig. 7	1550°F	79	86

Hence it is concluded that operation at 1660°F gave less efficient sulphur retention than at 1550°F.

At a fluidising velocity of 6.4 ft/s and a Ca/S mol ratio of 2.7, reducing the particle size of the limestone increased the SO_2 emission slightly, as shown

Test	Acceptor particle size (upper limit) micron	SO_2 reduction %	Sulphur retention %
3.1	3175	85	90
3.6	150	83	88

3.3.4 Nitrogen oxide emission

Values for the concentration of nitrogen oxides in the combustion products obtained by the Saltzman method are reported in Table 28.

3.3.5 Corrosion of metal specimens

The procedures used to examine and assess the metal specimens after the conclusion of the Test Series were identical with those used in Test Series 2. Estimates of the rates of corrosion are given in Table 31: the results of the microscopic examination of a few selected medium carbon steel and ferritic steel specimens are reported in Table 22.

3.3.6 Mass Balances

Balances have been computed for ash, carbon, oxygen, nitrogen, sulphur, calcium and magnesium for tests 3.6 and 3.7. These are presented in Tables 43 and 44 respectively.

3.4 Test Series 4

3.4.1 Objectives of the Test Series

To assess the effect of bed temperatures, and Ca/S mol ratio on sulphur retention when dolomite was fed to the fluid-bed.

3.4.2 Description of Test Series 4

Test Series 4 was run for a total of 100 h from 19th April to 23rd April 1971. The plant shut down for 1¼ hours on the second day due to the tripping of a thermal overload in the main switch to the coal weigher. The cause of this was an unusually high ambient temperature. Thereafter the switch was cooled with compressed air.

Nine tests were carried out, the first seven having a duration of four hours each with a six hour interval between tests to allow conditions to stabilize. The last test period continued for five hours and was divided into two separate tests. The operating conditions set during the test series are shown diagrammatically in Fig. 10 and tabulated in Table 32.

A constant fluidising velocity of 8.2 ft/s and a coal rate of about 240 lb/h were used throughout the test series. Limestone 18, sized -3175 micron was fed to the bed during Test 3.1. Thereafter, the SO_2 acceptor was Dolomite 1337, sized -1587 micron.

Because of the short duration of the test series, corrosion probes were not installed in the fluid-bed.

The size grading of the coal used during the test series is given in Table 33 and the chemical composition in Table 3. Chemical analysis and size of the bed extract samples and the cyclone fines are tabulated in Table 34 and 35 respectively. Gas composition data, together with bed temperatures in the bed at four heights above the distributor plate, are given in Table 36. Mass flow rate data for the input and output air and solids are summarised in Table 37.

3.4.3 Sulphur emission

The concentration of sulphur dioxide in the combustion products was determined during each of the 9 tests in Test Series 4 by the chemical method. These values are tabulated in Table 36 and have been used to calculate the values of SO_2 reduction and sulphur retention which are given in Table 38. In calculating SO_2 reduction the level of sulphur dioxide in combustion products, found during Test Series 1 (viz. 2050 ppm SO_2 v/v) when no acceptor was fed to the fluid bed, has been used as the sulphur dioxide concentration at zero reduction.

Comparisons are made in Table 39 of the effect of bed temperature and Ca/S mol ratio on sulphur retention and SO_2 reduction when dolomite was added to the fluid-bed. At 0.65 Ca/S mol ratio, increasing bed temperature from 1425° to 1680°F resulted in an almost linear decrease in SO_2 reduction, Fig. 11. However, at a Ca/S mol ratio of 1.8, the relation between bed temperature and SO_2 reduction was curved having a maximum at about 1500°F and declining rapidly at temperatures in excess of 1575°F.

Other comparisons which can be drawn from Test Series 4 are reported in Table 39 and include the effect of acceptor type, bed weight and external recycle of fines on sulphur reduction. At 1425°F, the calcium oxide obtained from the -1587 micron dolomite was a more effective acceptor of sulphur dioxide than the calcium oxide obtained from -3175 micron limestone. As in previous tests with limestone, increasing bed height by about 30% during operation with dolomite addition did not have a noticeable effect on sulphur reduction or retention. External fines recycle during operation with -1587 micron dolomite at 1540°F had a pronounced effect on the amount of acceptor needed to achieve a SO_2 reduction of 80%.

3.4.4 Nitrogen oxide emission

The values reported in Table 36 for concentration of nitrogen oxides in the combustion products were determined by the Saltzman method.

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Chemical analyses were carried out in the BCURA Analytical Section under the direction of R.G. James.

Table A3.1. Operating conditions during Test Series 1

Coal	Pittsburgh
Coal size (upper limit)	3175 µm
Coal rate	229 lb/h
Acceptor	Nil
Fluidising velocity	8.0 ft/s
Bed temperature	1512°F

Table A3.2. Test Series 1b (500h). Chemical analysis and size grading of coal

Test period, h		0–100	100–200	200–300	300–400	400–500
Total moisture	% a.r.	1.9	2.7	1.9	1.9	–
A.D.B. moisture	% air dried	1.5	1.3	1.4	1.5	1.5
Ash	% air dried	12.4	14.5	13.5	13.5	14.2
Volatile matter	% daf	41.5	41.4	41.1	41.0	41.6
Calorific value	Btu/lb d.a.f.	15090	15050	15030	15080	15090
Size Grading	% within stated size grade					
–6350 + 3175 µm		0	0	0	0	0
–3175 + 1588 µm		33	31	32	30	31
–1588 + 794 µm		25	27	28	26	26
– 794 + 500 µm		11	12	12	12	13
– 500 + 211 µm		14	14	13	15	14
– 211 + 152 µm		3	3	3	4	3
– 152 + 75 µm		5	5	5	5	5
– 75 + 0 µm		9	8	7	8	8

Table A3.3. Chemical analysis of bulk samples of coal

Test Series		1b	2	3	4
Moisture	% air dried	1.5	1.7	1.5	1.5
Ash	% air dried	13.8	13.1	13.6	11.0
Volatile matter	% daf	41.0	41.7	41.2	40.8
Carbon dioxide	% air dried	0.7	0.7	0.6	0.4
Ash	% db	14.0	13.3	13.8	11.2
Carbon	% db	72.1	72.0	72.2	74.6
Hydrogen	% db	4.7	4.9	4.9	5.1
Nitrogen	% db	1.2	1.1	1.1	1.4
Sulphur	% db	3.0	3.1	2.9	2.5
Oxygen + errors	% db	5.0	5.5	5.1	5.2
Chlorine	% db	-	0.07	-	-
Ash analysis					
CaO	%	-	-	7.1	7.5
MgO	%	-	-	1.7	1.9
Ash fusion (in air)					
Initial deformation	°F	2265	2210	2255	2200
Hemisphere	°F	2335	2315	2310	2310
Flow	°F	2445	2445	2390	2420
Calorific value	Btu/lb daf	-	15100	15050	15070
Swelling no.	-	8	6½	8	8
Gray King Coke	-	G9	G9	G9	G9

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Table [illegible]. Test Series [illegible] (500h). Chemical and size analysis of bed extract

Test period, h	0-100	100-200	200-300	300-400	400-500
Chemical analysis					
Combustible, % a.r.	2.9	1.8	1.3	1.3	1.2
Size grading	% within stated size grade				
-6350 + 3175 µm	0	0	0	1	0
-3175 + 1587 µm	27	30	29	29	30
-1587 + 794 µm	38	39	38	37	37
- 794 + 500 µm	21	20	21	21	21
- 500 + 211 µm	10	8	8	8	9
- 211 + 152 µm	1	1	1	1	1
- 152 + 75 µm	2	1	2	2	1
- 75 + 0 µm	1	1	1	1	1

Table A3.5. Test Series 1b (500h). Chemical and size analysis of cyclone fines

Test period, h	0–100	100–200	200–300	300–400	400–500
Chemical analysis					
Combustible, % a.r.	51.5	53.5	54.3	58.1	58.0
Size grading	% within stated size grade				
−6350 + 3175 μm	0	0	0	0	0
−3175 + 1587 μm	0	0	0	0	0
−1587 + 794 μm	0	1	0	0	0
− 794 + 500 μm	2	3	2	1	1
− 500 + 211 μm	13	11	10	12	13
− 211 + 152 μm	6	7	6	9	9
− 152 + 75 μm	24	25	25	26	26
− 75 + 0 μm	55	54	57	52	51

Table A3.6. Test Series 1b (500h). Chemical and size analysis of exhaust dust

Test period, h	0-100		100-200	200-300	300-400	400-500
	(1)	(2)				
Chemical analysis						
Combustible, % a.r.	20.6	20.0	20.9	20.4	20.4	23.1
Size grading	% within stated size grade					
−75 + 60 μm	0	0	0	6	0	0
−60 + 50 μm	0	0	0	0	0	0
−50 + 40 μm	0	0	0	1	0	0
−40 + 30 μm	3	1	1	3	4	4
−30 + 20 μm	6	5	5	9	8	11
−20 + 10 μm	25	19	22	22	33	31
−10 + 5 μm	51	52	51	41	36	35
− 5 + 0 μm	15	23	21	18	19	19
Median diameter μm	8	7	7	9	9	9
Mean diameter D_p, μm	8	7	7	8	8	8

D_p is given by $1/D_p = \Sigma x_{ij}/(d_i d_j)^{0.5}$, where x_{ij} is the weight fraction between particle size limits d_i and d_j micron

Table A3.7. Test Series 1b (500 h). Performance data

Test period, h		0– 100	100– 200	200– 300	300– 400	400– 500
Gas composition						
O_2	% v/v	3.1	3.5	3.2	2.9	3.3
CO_2		14.3	14.6	14.9	14.6	14.7
CO	(dry gas)	0.77	0.75	0.78	0.71	0.58
SO_2	% v/v	2045	2110	2045	2105	1960
NO_x	(dry gas)	480	340	–	610	670
Bed temperature Height above distributor plate						
3 in	°F	1508	1506	1505	1509	1503
9 in	°F	1509	1505	1508	1512	1512
15 in	°F	1512	1508	1510	1514	1513
21 in	°F	1514	1515	1521	1523	1525
Mean temperature	°F	1511	1508	1511	1515	1513

Unburnt carbon	16%
Excess air	2.2%

Table A3.8. Test Series 1b (500h). Mass flows and potential heat losses in solids

Air		
Through distributor plate	lb/h	1980
Coal conveying	lb/h	218
Recycle of fines from external cyclone	lb/h	71
Total	lb/h	2270
Coal		
Input rate	lb/h	229
Approx. calorific value	Btu/lb	12750
Bed extract		
Rate	lb/h	6.2
Combustible	%	1.7
Approx. heat loss	%	0.05
Cyclone fines rejected		
Rate	lb/h	44.7
Combustible	%	55.7
Approx. heat loss	%	12.4
Dust in cyclone exit		
Rate	lb/h	9.6
Combustible	%	20.8
Approx. heat loss	%	1.0

Table A3.9. Test Series 1, Sulphur dioxide content of combustion products

Test Series	No.	Date	SO_2 ppm
1a	1	12th and 13th Nov. 1970	2070
	2		2090
	3		2060
	4		2000
	5		2020
	6		2110
1b	7	17.11.70	2020
	8		2250
	9	20.11.70	1970
	10		1910
	11		1960
	12		2170
	13	23.11.70	2190
	14		2110
	15		2050
	16		2100
	17	26.11.70	1970
	18		2050
	19		2050
	20		2110
	21	1.12.70	2080
	22		2130
	23		2110
	24		2100
	25	4.12.70	2120
	26		2090
	27	7.12.70	1850
	28		1840
	29		1970

Table A3.10. Test Series 1b (500h). Weight losses for corrosion specimens

Weight loss is given in $\mu g/cm^2h$

Tube No.	Location of ring	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x
1	Alloy	R	R	W	S	R	S	W	E	S	E	R	S	E	W	S	R	W	E	S	W	R	E	W	E
	Weight loss	13.1	3.5	4.5	13.3	2.9	7.6	6.0	18.5	5.7	12.2	12.3	9.9	10.8	3.3	13.5	8.3	3.7	21.3	8.4	4.3	14.7	11.8	3.5	21.5
	Temp. °F	←1290→																							
2	Alloy	R	S	R	S	R	E	T	E	T	W	S	S	S	W	E	E	W	R	R	W	T	T	W	E
	Weight loss	5.9	2.7	1.1	4.3	5.0	7.3	603	8.4	380	2.1	2.1	4.1	3.1	3.3	6.7	5.7	2.1	1.9	6.2	2.3	707	632	4.6	9.1
	Temp. °F	← 1110 →																							
3	Alloy	R	T	W	T	R	S	R	E	T	C	T	E	S	E	S	C	W	C	E	W	E	R	W	C
	Weight loss	6.6	439	7.8	449	2.8	3.8	2.3	6.8	254	435	606	11.0	3.5	3.0	5.9	301	6.1	464	6.1	6.4	7.1	9.2	8.8	413
	Temp. °F	← 930 →																							
4	Alloy	R	T	W	T	R	S	R	E	T	C	T	E	S	E	S	C	W	C	E	W	E	R	W	C
	Weight loss	7.2	53.1	4.1	111	3.6	1.5	7.6	4.2	300	55.1	96.0	6.7	1.5	0.7	4.3	40.6	2.9	*	1.4	4.3	5.1	0.4	4.4	800
	Temp. °F	← 750 →																							

* 614 $\mu g/cm^2h$, obviously a spurious reading

R	Austenitic type 347	W	Ferritic 12% Cr steel
S	Austenitic type 316	T	Ferritic 2¼% Cr 1% Mo steel
E	Austenitic type Esshete 1250	C	Ferritic Medium C steel

Table A3.11. Test Series 2 (1000 h) Operating conditions during test series

Constant Parameters	
Coal	Pittsburgh
Coal size (upper limit)	3175 μm for Tests 2.1 to 2.3, and 2.11 to 2.16: 150 μm for Tests 2.4 to 2.9.
Acceptor	U.S. limestone 18
Coal rate	234 lb/h
Fluidising velocity	8.1 ft/s
Bed temperature	1548°F

Variable parameters	Test No.	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9.1	2.9.2	2.10	2.11	2.12	2.13	2.14	2.15	2.16.1	2.16.2
Time elapsed from start of test series (h)	Start	39	113	170	231	300	360	399	484	517	541	603	671	731	805	851	911	951	975
	End	55	139	184	256	316	376	435	493	523	547	619	687	747	813	867	927	959	983
Acceptor size - micron (upper limit)		3175	3175	3175	150	150	150	150	150	150	150	-	3175	3175	3175	3175	3175	3175	3175
Ca/S mol ratio		1.58	0.44	3.09	1.86	0.88	2.46	0.74	2.47	1.63	1.45	0	1.09	2.37	3.89	0.62	2.45	1.93	2.47
Recycle of cyclone fines		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	No	No
Bed weight - lb		250	270	220	210	210	220	230	240	310	250	270	260	220	210	270	210	280	210

Table A3.12. Test Series 2 (1000 h) Chemical analysis of coal

Test period, h		100 h 2.1	200 h 2.2-2.3	300 h 2.4	400 h 2.5-2.6	500 h 2.7-2.8	600 h 2.9.1-2.9.2	700h 2.10-2.11	800 h 2.12	900 h 2.13-2.14	1000 h 2.15-2.16
Proximate analysis											
Moisture	% air dried	1.8	1.8	1.7	1.9	1.9	1.6	1.3	1.9	1.7	1.8
Ash	% air dried	13.2	13.7	12.7	13.4	13.4	11.0	12.7	15.4	15.0	10.4
Volatile matter	% daf	40.8	40.6	41.2	41.1	41.5	41.4	41.5	41.2	41.7	41.2
Calorific value	Btu/lb d.a.f.	15050	-	15080	15170	15120	15110	14980	15070	15090	15080
Size grading		% within stated size grade									
-6350 + 3175 µm		1	1	2	1	1	-	1	1	3	2
-3175 + 1587 µm		25	22	25	23	27	-	39	30	26	44
-1587 + 794 µm		17	26	28	27	28	-	26	26	24	25
- 794 + 500 µm		12	14	12	14	11	-	9	11	13	8
- 500 + 211 µm		16	19	15	16	15	-	12	15	15	9
- 211 + 152 µm		14	3	4	4	4	-	3	3	4	3
- 152 + 75 µm		6	6	5	6	6	-	4	6	8	3
- 75 + 0 µm		9	9	9	9	8	-	6	8	7	6

No size grading is available for sample for period 500-600 h.

Table A3.13. Chemical analysis and size grading of additives

Additive		Limestone 18		Dolomite 1337
Chemical composition				
SiO_2	%	13.6		-
Al_2O_3	%	0.5		-
Fe_2O_3	%	0.3		-
CaO	%	45.7		29.4
MgO	%	1.4		21.4
Na_2O	%	0.2		0.5
K_2O	%	0.1		0.1
CO_2	%	36.6		45.8
Total	%	98.4		97.2
Size grading		$-\frac{1}{8}$ in	-100 BS mesh	$-\frac{1}{16}$ in
-6130 + 3175 µm	% within stated size grade	1		-
-3175 + 1587 µm		46		0
-1587 + 794 µm		21		74
- 794 + 500 µm		9		16
- 500 + 211 µm		11		3
- 211 + 152 µm		3		1
- 152 + 75 µm		4		2
- 75 + 0 µm		5	100	4

Table A3.14. Test Series 2. Chemical and size analysis of bed extract

Test No.	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9.1	2.9.2	2.10	2.11	2.12	2.13	2.14	2.15	2.16.1	2.16.2
Combustible	2.4	3.8	0.9	3.4	2.8	4.9	2.4	4.2	3.0	0.7	0.7	1.8	1.5	3.6	2.2	4.2	3.0	1.4	2.3
Sulphur	–	7.5	8.1	8.1	–	–	2.8	2.7	2.4	2.3	2.3	2.4	8.3	3.8	3.5	7.0	6.5	9.1	9.0
CaO	–	38.9	31.4	47.3	–	–	14.6	15.0	16.5	12.4	12.4	11.8	34.7	40.1	44.4	29.0	38.1	43.0	44.4
MgO	–	0.6	0.9	0.8	–	–	1.9	2.8	1.9	2.1	2.1	2.0	1.5	1.4	1.3	2.2	2.0	2.0	1.3
Particle size analysis	% within stated size grade																		
-6350 + 3175µm	1	1	2	1	1	2	1	1	1	1	1	2	1	0	0	1	0	1	0
-3175 + 1587µm	17	29	31	25	27	19	17	16	26	40	40	30	22	0	14	21	5	23	12
-1587 + 794µm	38	36	37	37	39	30	35	27	33	33	33	33	34	19	26	29	15	41	40
-794 + 500µm	26	18	19	22	18	17	22	21	18	14	14	18	21	27	26	17	19	27	37
-500 + 211µm	15	11	9	11	6	12	13	16	10	1	1	12	16	31	22	19	32	6	9
-211 + 152µm	1	2	1	2	1	4	2	4	1	0	0	2	4	12	8	5	15	1	1
-152 + 75µm	1	2	1	1	4	10	7	10	7	0	0	2	2	9	3	7	13	1	1
- 75 + 0µm	1	1	0	1	4	6	3	5	4	0	0	1	0	2	1	1	1	0	0

Analyses are stated as weight percent on an "as received" basis

Table A3.15 Test Series 2 (1000 h). Chemical and size analyses of cyclone fines

Test No	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9.1	2.9.2	2.10	2.11	2.12	2.13	2.14	2.15	2.16.1	2.16.2
Combustible	45.2	41.9	50.7	29.7	30.2	28.4	23.3	25.2	22.8	37.6	37.6	43.2	40.6	29.0	22.6	38.1	26.7	40.7	36.6
Sulphur	-	-	-	-	-	-	3.1	2.8	3.0	1.7	1.7	1.0	2.7	3.8	5.8	2.6	2.6	-	4.1
CaO	-	-	-	-	-	-	31.4	21.1	31.4	22.6	22.6	5.9	14.0	27.4	33.7	12.7	29.0	-	22.6
MgO	-	-	-	-	-	-	1.2	0.6	1.2	0.8	0.8	0.8	0.9	1.1	1.4	1.1	0.9	-	1.1
Size grading	% within stated size grade																		
-3175 + 1587μm	0	0								0	0								
-1587 + 794μm	1	1	0	0	0	0	0	0	0	1	1	0	0						0
- 794 + 500μm	1	1	1	1	1	1	1	1	1	2	2	1	1	0	0	0	0	0	1
- 500 + 211μm	13	20	13	19	6	5	4	7	5	10	10	6	13	12	17	12	1	2	3
- 211 + 152μm	8	10	9	13	4	4	5	4	4	7	7	7	9	10	14	8	11	19	25
- 152 + 75μm	25	25	27	23	20	21	22	19	22	25	25	18	24	22	23	21	9	12	14
- 75 + 0μm	52	43	50	44	69	69	68	69	68	55	55	68	53	56	46	59	30	25	29

Analyses are stated as weight percent on an "as received" basis

Table A3.16. Test Series 2 (1000 h). Analysis of exhaust dust

Test No.	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.9.1	2.9.2	2.10	2.11	2.12	2.13	2.15
Combustible	20.2	19.8	17.5	13.4	16.3	13.1	16.1	7.2	8.1	28.3	18.4	20.1	16.2	20.0
Sulphur	3.3	1.7	4.2	5.8	4.3	6.4	4.3	8.4	8.5	1.2	-	-	-	-
CaO	12.7	5.0	24.2	28.9	21.9	36.0	21.6	37.5	35.1	4.3	10.0	19.1	27.3	18.1
MgO	0.9	0.9	1.0	1.0	1.0	1.1	1.0	1.1	1.0	0.7	-	-	-	-
Size grading	% within stated size grade													
– 78 + 64µm							1		1					
– 62 + 49µm			1			1	1		1		1			1
– 49 + 42µm			1	2		2	0	2	2		1	1	1	0
– 42 + 33µm	0	0	0	0		1	1	1	2		1	1	0	1
– 33 + 26µm	2	2	3	3		2	3	2	5	2	3	2	2	2
– 26 + 21µm	3	6	4	7	2	4	4	2	9	3	5	3	4	3
– 21 + 17µm	7	3	5	8	8	4	7	4	17	6	4	5	5	4
– 17 + 13µm	6	8	8	10	7	7	7	6	12	11	7	6	6	7
– 13 + 11µm	10	9	11	12	11	10	13	8	13	15	8	11	10	11
– 11 + 9µm	13	11	11	12	14	11	11	11	7	17	11	11	12	15
– 9 + 7µm	13	11	13	10	13	13	12	12	6	14	11	15	13	13
– 7 + 0µm	46	50	43	36	45	45	39	52	25	32	48	45	47	43
Mean diameter, µm	8	7	8	9	8	8	9	8	11	9	8	8	8	8
Median diameter, D_p, µm	8	7	8	9	8	8	9	7	13	9	8	8	8	8

Analyses are given as weight percent on an "as received" basis

No samples of exhaust dust were taken during Tests 2.8, 2.14 and 2.16

D_p is given by $1/D_p : \Sigma x_{ij}/(d_i d_j)^{0.5}$ where x_{ij} is the fraction by weight between particle size limits d_i and d_j micron.

Table A3.17. Test Series 2 (1000 h) Performance data

Test No		2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9.1	2.9.2	2.10	2.11	2.12	2.13	2.14	2.15	2.16.1	2.16.2
Elapsed time from start of test series, h	Start	39	113	170	231	300	360	399	484	517	541	603	671	731	805	851	911	951	975
	End	55	139	184	256	316	376	435	493	523	547	619	687	747	813	867	927	959	983
Operating conditions																			
Ca/S mol ratio		1.58	0.44	3.09	1.86	0.88	2.47	0.74	2.47	1.63	1.45	0	1.09	2.37	3.89	0.62	2.45	1.93	2.47
Acceptor size (upper limit) μm		3175	3175	3175	150	150	150	150	150	150	150	–	3175	3175	3175	3175	3175	3175	3175
Recycle		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	No	No
Bed weight, lb.		250	270	220	210	210	220	230	240	310	250	270	260	220	210	270	210	280	210
Unburnt carbon %		14	16	16	14	9	11	8	>7	>20	>7	>6	13	12	11	>9	11	>16	>16
Excess air %		-1.8	-1.2	-4.4	2.7	4.2	4.4	6.6	3.8	-1.2	29.1	5.5	-4.1	1.4	0.5	-0.7	-8.0	-11.2	15.7
Gas composition																			
CO_2 % v/v		14.3	14.1	14.3	14.6	14.8	14.1	14.7	13.9	14.3	11.9	14.9	16.2	15.2	16.9	14.8	15.4	13.7	10.7
CO % v/v		0.66	0.68	0.69	0.66	0.65	0.72	0.69	0.71	0.54	0.57	0.7	0.68	0.71	0.67	0.75	0.71	0.64	0.48
O_2 % v/v		3.7	3.5	2.8	3.9	3.5	3.8	3.9	3.8	4.2	7.6	3.5	3.4	3.6	3.6	3.6	3.8	4.0	7.6
SO_2 ppm v/v		930	1760	290	1370	1520	830	1610	790	1110	940	1680	1220	500	310	1550	530	910	680
NO_x ppm v/v		430	–	–	–	380	490	500	390	–	–	–	–	490	200	500	–	–	–
Bed temperature, °F Height above distributor plate,																			
3 in		1495	1499	1531	1555	1573	1546	1555	1566	1549	1542	1557	1553	1553	1558	1531	1560	1535	1519
9 in		1495	1499	1531	1571	1573	1553	1555	1573	1566	1567	1569	1557	1553	1564	1539	1562	1535	1524
15 in		1506	1513	1539	1576	1587	1569	1567	1584	1573	1580	1582	1566	1567	1573	1555	1580	1544	1546
21 in		1508	1513	1529	1542	1555	1535	1539	1560	1569	1492	1575	1557	1546	1551	1560	1575	1544	1501
Mean temperature		1501	1507	1533	1561	1572	1551	1554	1571	1564	1545	1571	1558	1554	1561	1546	1564	1500	1523

Table A3.18. Test Series 2 (1000 h) Mass Flows (lb/h)

Test No	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9.1	2.9.2	2.10	2.11	2.12	2.13	2.14	2.15	2.16.1	2.16.2
Air input																		
Through distributor plate	1980	1980	1980	1980	1980	1980	1960	1980	1980	1980	1980	1990	1980	1980	1980	1980	1980	1960
Coal conveying	21[illegible]	213	217	212	209	212	214	216	216	205	216	216	220	223	220	212	216	216
External fines recycle	77	71	75	73	71	73	75	73	75	75	75	75	73	86	86	82	88	88
Total	2270	2260	2270	2270	2260	2270	2250	2270	2270	2260	2270	2280	2270	2290	2290	2270	2280	2260
Coal input	239	238	247	227	225	227	229	227	231	176	220	243	238	243	240	247	256	196
Limestone input	44	12	88	50	23	65	20	65	45	33	Nil	31	64	108	17	73	60	58
Bed extract	26	13	36	9	5	5	5	6	4	3	2	17	36	44	16	45	17	7
Cyclone fines rejected	53	52	84	66	34	61	39	47	91	40	23	51	51	63	38	60	73	66
Exhaust dust	9	8	11	18	22	33	20	12	-	6	-	11	19	19	-	14	-	-

Table A3.19 Test Series 2 (1000 h). Effect of operating conditions on sulphur retention and SO_2 reduction

Test	Limestone	Bed wt. lb	Bed Temp °F	Ca/S mol ratio	SO_2 in exit gas ppm v/v	Sulphur retention %	SO_2 Reduction %
2.1	Coarse	250	1501	1.58	925	69	55
2.2		270	1507	0.44	1760	42	14
2.3		220	1533	3.09	290	91	86
2.4	Fine	210	1561	1.86	1375	52	32
2.5		210	1572	0.88	1520	46	26
2.6		220	1551	2.47	835	71	59
2.7		230	1554	0.74	1615	44	21
2.8		240	1571	2.47	790	72	61
2.9.1		310	1564	1.63	1110	62	46
2.9.2		250	1545	1.45	940	57	54
2.10	Nil	270	1571	0	1680	40	18
2.11	Coarse	260	1558	1.09	1220	59	40
2.12		220	1554	2.37	500	83	76
2.13		210	1561	3.89	305	90	85
2.14		270	1546	0.62	1550	48	24
2.15		210	1564	2.45	530	83	74
2.16.1		280	1500	1.93	910	72	56
2.16.2		210	1523	2.47	680	72	67
1b	Nil	220	1512	0	2050	21	0

Coarse limestone was sized -3175 micron

Fine limestone was sized - 150 micron

Table A3.19A Test Series 2. Comparative assessments of SO_2 reduction

Test No.	Limestone	Bed Temp °F	Bed weight lb	Ca/S mol ratio	SO_2 ppm v/v	Excess air %	Corrected SO_2 ppm	SO_2 reduction*
Replicate Tests								
2.3	Coarse	1533	220	3.09	290	-4.4	280	86
2.13		1561	210	3.89	310	0.5	310	85
2.5	Fine	1572	210	0.88	1520	4.2	1585	23
2.7		1554	230	0.74	1610	6.6	1715	16
2.6	Fine	1551	220	2.47	830	4.4	865	58
2.8		1571	240	2.47	790	3.8	820	60
2.12	Coarse	1554	220	2.37	500	1.4	510	75
2.15		1564	210	2.45	530	-8.0	490	76
Effect of bed weight								
2.9.1	Fine	1564	310	1.63	1110	-1.2	1100	46
2.9.2		1545	250	1.45	940	29.1	1210	41
2.16.1	Coarse	1500	280	1.93	910	-11.2	810	60
2.16.2		1523	210	2.47	680	15.7	790	61
Effect of bed temperature								
2.2	Coarse	1507	270	0.44	1760	-1.2	1740	15
2.14		1546	270	0.62	1550	-0.7	1540	25

Coarse limestone was sized -3175 micron

Fine limestone was sized -150 micron

* Calculated from correct SO_2 and assuming 2050 ppm SO_2 v/v in combustion products when zero acceptor is fed to the bed

Table A3.20. Test Series 2 (1000 h). Nitrogen oxides emission in exit gas

Test	Date	Time h	NO_x ppm v/v	Mean No_x ppm v/v	Limestone addition	
					mean size micron	Ca/S mol ratio
2.1	21.1.71	15.40	418	428	3175	1.58
	21.1.71	15.50	456			
	22.1.71	11.30	419			
	22.1.71	11.50	420			
Between 2.3 and 2.4	28.1.71	12.00	296	297	-	0
		12.10	297			
2.5	1.2.71	15.00	329	378	150	0.88
		15.30	427			
2.6	4.2.71	11.40	424	488	150	2.47
		12.00	553			
2.7	5.2.71	11.15	494	497	150	0.74
		11.30	499			
2.8	9.2.71	10.00	382	386	150	2.47
		10.30	390			

Table A3.21 Test Series 2 (1000 h) Weight loss for corrosion specimens

Weight loss is given in μg/cm²h

Tube No.	Location of ring	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w
1	Alloy	S	E	E	R	R	W	W	W	S	R	R	E	S	S	W	W	E	R	R	W	S	S	E
	Weight loss	5.5	10.8	8.4	5.1	3.7	*	2.9	3.9	12.2	3.1	5.7	14.5	9.3	7.6	2.7	11.7	10.4	8.1	3.0	3.1	12.8	7.7	14.6
	Temp °F	----- 1290 -----																						
2	Alloy	S	E	S	R	W	R	W	E	E	T	E	R	S	R	T	W	T	S	R	S	W	T	W
	Weight loss	5.5	3.6	2.3	2.7	1.4	1.6	5.3	3.3	2.7	255	4.4	1.1	2.7	1.3	184	11.7	340	2.3	2.1	3.7	1.2	298	2.1
	Temp °F	----- 1110 -----																						
3	Alloy	S	R	S	R	W	T	C	W	R	S	E	T	E	W	S	W	T	C	R	E	E	T	C
	Weight loss	0.7	1.0	1.3	1.4	2.0	27.4	41.6	3.5	1.5	0.9	1.2	18.4	1.0	2.0	1.0	3.7	54.0	22.9	0.8	1.4	1.0	43.6	44.6
	Temp °F	----- 930 -----																						
4	Alloy	S	R	S	R	W	T	C	W	R	S	E	T	E	W	S	W	T	C	R	E	E	T	C
	Weight loss	0.3	0.5	1.0	1.4	0.3	8.3	11.3	2.7	0.5	0.3	1.5	5.5	0.8	1.7	0.5	2.5	11.4	7.7	1.0	1.2	0.7	9.8	12.5
	Temp °F	----- 750 -----																						

* Spurious reading

R	Austenitic type 347	W	Ferritic 12% Cr steel
S	Austenitic type 316	T	Ferritic 2¼% Mo steel
E	Austenitic type Esshete 1250	C	Ferritic medium C steel

Table A3.22. Microscopic examination of metal corrosion specimens

Test Series	Temp °F	Material	Surface texture	Penetration μm	
				Pits	Sulphur
2	750	C	smooth	-	-
		T	smooth	-	-
		W	smooth	-	-
		S	smooth	-	-
		R	smooth	-	-
		E	smooth	-	-
2	930	C	rough	v.slight	-
		T	rough	v.slight	-
		W	smooth	-	-
		S	smooth	-	-
		R	smooth	-	-
		E	smooth	-	v.slight
2	110	T	rough	some	70
		W	smooth	-	-
		S	rough	-	30
		R	smooth	-	5
		E	smooth	-	15
2	1290	W	smooth	-	v.slight
		S	rough	-	45
		R	smooth	-	5
		E	rough	-	25
3	750	C	smooth	-	-
3	930	T	smooth rough	-	-
		W	smooth	-	-

Code to materials

C = Ferritic medium C steel
I = Ferritic 2¼% Cr 1% Mo steel
W = Ferritic 12% Cr steel
S = Austenitic type 316
R = Austenitic type 347
E = Austenitic type Esshete 1250

Surface Texture

Smooth = surface irregularities of up to 4 μm
Rough = surface irregularities of up to 12 μm

Table A3.23. Test Series 3 (500 h) Operating conditions during Test Series

Constant Parameters								
Coal		Pittsburgh						
Coal size (upper limit)		3175 µm						
Variable Parameters	Test No.	3.1	3.2	3.3	3.4	3.5	3.6	3.7
Time elapsed from start of Test Series (h)[*]	Start	67	138	186	234	306	378	475
	End	83	154	202	250	322	394	490
Fluidising velocity	ft/s	6.4	10.8	6.6	10.9	8.2	6.4	8.2
Coal input rate	lb/h	190	278	183	287	222	185	229
Acceptor		Limestone 18						Dolomite
Acceptor size (upper limit) micron		3175	3175	3175	3175	3175	150	1337 1587
Acceptor input rate	lb/h	57	83	55	86	67	56	77
Ca/S mol ratio		2.68	2.69	2.80	2.63	2.67	2.66	1.74
Recycle		Yes	Yes	No	No	Yes	Yes	Yes
Bed weight	lb	220	210	220	260	200	260	250
Bed temperature	°F	1550	1550	1547	1553	1659	1563	1549

Table A3.22. Microscopic examination of metal corrosion specimens

Test Series	Temp ^oF	Material	Surface texture	Penetration µm	
				Pits	Sulphur
2	750	C T W S R E	smooth smooth smooth smooth smooth smooth	- - - - - -	- - - - - -
2	930	C T W S R E	rough rough smooth smooth smooth smooth	v.slight v.slight - - - -	- - - - - v.slight
2	110	T W S R E	rough smooth rough smooth smooth	some - - - -	70 - 30 5 15
2	1290	W S R E	smooth rough smooth rough	- - - -	v.slight 45 5 25
3	750	C	smooth	-	-
3	930	T	smooth rough	-	-
		W	smooth	-	-

Code to materials

C = Ferritic medium C steel
T = Ferritic 2¼% Cr 1% Mo steel
W = Ferritic 12% Cr steel
S = Austenitic type 316
R = Austenitic type 347
E = Austenitic type Esshete 1250

Surface Texture

Smooth = surface irregularities of up to 4 µm
Rough = surface irregularities of up to 12 µm

Table A3.24. Test Series 3 (500 h). Chemical analysis and size grading of coal

Test period, h		0 - 100	100-200	200-300	300-400	400-500
Proximate analysis						
Moisture	% air dried	1.5	1.6	1.4	1.5	1.5
Ash	% air dried	11.6	12.1	13.4	11.5	12.3
Volatile matter	% daf	41.2	41.2	40.8	41.4	41.0
Calorific value	Btu/lb daf	15180	15120	15120	15060	14960
Size grading		% within stated size grade				
−6350 + 3175 μm		1	0	1	1	1
−3175 + 1587 μm		31	29	23	24	29
−1587 + 794 μm		29	27	26	26	28
− 794 + 500 μm		11	11	13	12	11
− 500 + 211 μm		13	15	16	15	14
− 211 + 75 μm		5	5	6	6	5
− 75 + 0 μm		7	9	10	9	8

Table A3.25. Test Series 3 (500 h). Chemical and size analysis of bed extract

Test No.	3.1	3.2	3.3	3.4	3.5	3.6	3.7
Chemical analysis							
Combustible	2.3	2.4	1.7	1.2	2.4	2.5	4.5
CaO	44.5	46.5	42.4	45.4	38.1	17.1	27.1
MgO	1.4	3.0	2.1	1.7	1.8	1.7	15.0
Sulphur	7.3	7.8	7.1	5.9	4.2	3.3	6.8
Size grading	% within stated size grade						
-6350 + 3175 µm	0	0	0	0	0	1	1
-3175 + 1587 µm	6	25	17	34	10	26	21
-1587 + 794 µm	18	39	28	52	23	35	47
- 794 + 500 µm	22	9	19	12	16	21	14
- 500 + 211 µm	31	15	26	1	28	12	7
- 211 + 152 µm	17	7	6	1	13	1	2
- 152 + 75 µm	5	4	3	0	8	3	5
- 75 + 0 µm	1	1	1	0	2	1	3

Analyses are stated as weight per cent on an "as received" basis

Table A3.26. Test Series 3 (500 h). Chemical and size analysis of cyclone fines

Test No.	3.1	3.2	3.3	3.4	3.5	3.6	3.7
Chemical analysis							
Combustible	27.0	23.2	30.4	29.4	19.4	24.6	28.1
Sulphur	-	-	3.1	3.2	3.6	2.4	3.9
CaO	-	-	26.2	26.7	34.1	33.0	26.0
MgO	-	-	1.3	0.9	2.7	0.7	17.1
Size grading	% within stated size grade						
-794 + 500 µm	0	1	1	4	1	1	1
-500 + 211 µm	9	13	18	20	11	7	8
-211 + 152 µm	11	13	13	12	10	5	6
-152 + 75 µm	21	20	21	19	18	26	26
- 75 + 0 µm	59	53	47	45	60	61	59

Analyses are stated as weight per cent on an "as received" basis

Table A3.27 Test Series 3 (500 h) Chemical and size analysis of exhaust dust

Test No.	3.1	3.2	3.3	3.4	3.5	3.6	3.7
Chemical analysis							
Combustible	18.8	20.1	10.7	13.2	12.5	12.3	17.4
Sulphur	-	-	-	-	-	6.5	2.5
CaO	18.1	36.4	20.1	18.4	48.6	47.8	10.4
MgO	-	-	-	-	-	3.4	5.5
Size grading	% within stated size grade						
-69 + 49 μm				1		-	-
-49 + 42 μm	2	2		1		-	-
-42 + 33 μm	1	0		1	2	-	-
-33 + 26 μm	5	0	1	2	3	-	-
-26 + 21 μm	5	4	1	4	3	-	-
-21 + 17 μm	8	2	2	5	5	-	-
-17 + 13 μm	9	4	2	7	7	-	-
-13 + 11 μm	11	6	2	9	14	-	-
-11 + 9 μm	12	8	4	10	9	-	-
-9 + 7 μm	12	11	17	10	8	-	-
-7 + 0 μm	35	63	71	50	49	-	-
Median diameter μm	9	7	6	7	7	-	-
Mean diameter D_p μm	9	7	6	8	8	-	-

Analyses are given as weight percent on an "as received" basis.
D_p is given by $1/D_p = \Sigma x_{ij}/(d_i d_j)^{0.5}$, where x_{ij} is the weight fraction between particle size limits d_i and d_j micron.

Table A3.28. Test Series 3 (500 h). Performance data

Test No.		3.1	3.2	3.3	3.4	3.5	3.6	3.7
Elapsed time from start of Test Series h	Start	67	138	186	234	306	378	475
	End	83	154	202	250	322	394	490
Operating conditions								
Ca/S mol ratio		2.68	2.69	2.80	2.63	2.67	2.66	1.74
Acceptor size (upper limit) μm		3175	3175	3175	3175	3175	150	1587
Recycle		Yes	Yes	No	No	Yes	Yes	Yes
Bed weight, lb		220	210	220	260	200	260	250
Unburnt carbon	%	10	8	12	15	6	14	15
Excess air	%	-5.2	8.8	-2.4	7.4	2.8	-3.8	0.6
Gas composition								
CO_2 % v/v		13.2	14.9	14.9	13.5	14.0	14.5	14.3
CO % v/v		0.69	0.65	0.63	0.57	0.64	0.72	0.63
O_2 % v/v		3.7	5.2	5.1	6.1	4.4	3.6	4.4
SO_2 ppm v/v		300	480	380	480	860	340	640
NO_x ppm v/v		–	330	470	410	500	470	530
Bed temperature, °F								
Height above distributor plate								
3 in		1528	1560	1555	1539	1679	1562	1549
9 in		1528	1569	1558	1553	1681	1569	1557
15 in		1533	1585	1560	1558	1681	1575	1562
21 in		1513	1573	1515	1564	1593	1548	1528
Mean		1525	1572	1547	1553	1659	1563	1549

Table A3.29. Test Series 3 (500 h). Mass Flows (lb/h)

Test No.	3.1	3.2	3.3	3.4	3.5	3.6	3.7
Air Input							
Through distributor plate	1500	2730	1470	2730	1980	1480	1980
Coal conveying	214	212	216	216	216	214	216
External fines recycle	84	82	84	84	84	86	82
Total	1800	3020	1770	3030	2280	1780	2280
Coal input	190	278	183	287	222	185	229
Acceptor input	57	83	57	83	67	56	69
Bed extract	37	14	34	28	24	2.4	13
Cyclones fines rejected	44	50	52	108	41	65	82
Exhaust dust	10	23	4	3.5	14	21	13

Table A3.30. Test Series 3. Effect of operating conditions on sulphur retention and SO_2 reduction

Test No.		3.1	3.2	3.3	3.4	3.5	3.6	3.7
Fluidising velocity, ft/s		6.4	10.8	6.6	10.9	8.2	6.4	8.2
Acceptor		←----- Limestone -----→						Dolomite 1337
Acceptor size (upper limit) micron		3175	3175	3175	3175	3175	150	1587
Ca/S mol ratio		2.68	2.69	2.80	2.63	2.67	2.66	1.74
Recycle		Yes	Yes	No	No	Yes	Yes	Yes
Bed weight	lbs	220	210	220	260	200	260	250
Bed temperature	°F	1550	1550	1547	1553	1659	1563	1549
Sulphur retention	%	90	80	85	81	66	88	76
SO_2 reduction	%	85	77	82	77	58	83	69

Table A3.31. Test Series 3 (500 h). Weight loss for corrosion specimens

Weight loss is given in $\mu g/cm^2h$

Tube No	Location of rig	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w
1	Alloy	T	E	S	R	W	R	W	S	E	T	E	R	S	R	T	W	S	S	R	E	W	T	W
	Weight loss	7.8	1.1	1.1	0.7	3.1	0.9	2.2	0.8	1.1	36.7	1.4	1.1	1.2	1.0	27.1	2.1	1.3	1.0	1.3	1.4	2.1	49.8	2.2
	Temp °F	<—— 930 ——>																						
2	Alloy	R	C	S	S	W	T	C	W	C	S	E	T	E	W	S	W	T	R	R	E	E	T	R
	Weight loss	0.7	1.3	0.7	0.9	2.5	2.7	19.1	1.9	8.6	1.0	1.0	8.4	1.3	2.7	1.2	2.3	18.4	1.3	1.0	1.0	1.4	16.6	0.8
	Temp °F	<—— 750 ——>																						

R Austenitic type 346
S Austenitic type 316
E Austenitic type Esshete 1250

W Ferritic 12% Cr steel
T Ferritic 2¼% Cr 1% Mo steel
C Ferritic medium C steel

Table A3.32. Test Series 4. Operating conditions.

Constant Parameters										
Coal		Pittsburgh								
Coal size (upper limit)		3175 micron								
Fluidising velocity		8.2 ft/s								
Variable Parameters	Test No.	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9
Time elapsed from start of Test Series (h)	Start	22	36	46	56	66	76	86	96	99
	End	26	40	50	60	70	80	90	99	101
Coal input rate	lb/h	238	238	240	243	247	251	227	251	216
Acceptor* Acceptor size* (upper limit), µm		L	D	D	D	D	D	D	D	D
Acceptor input rate, lb/h		66	66	66	22	22	66	22	176	176
Ca/S mol ratio		2.94	1.89	1.88	0.62	0.61	1.79	0.66	4.78	5.56
Recycle		Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No
Bed weight, lb.		350	310	210	230	200	180	250	200	210
Bed temp. °F		1428	1418	1535	1564	1678	1680	1426	1645	1549

* L = Limestone 18, sized -3175 micron

D = Dolomite 1337, sized -1587 micron

Table A3.33. Test Series 4 (100 h). Size grading of coal

Particle size	% within stated size range
-6350 + 3175 µm	2
-3175 + 1587 µm	31
-1587 + 794 µm	27
- 794 + 500 µm	11
- 500 + 211 µm	14
- 211 + 152 µm	3
- 152 + 75 µm	5
- 75 + 0 µm	7

Table A3.34. Test Series 4 (100 h). Chemical and size analysis of bed extract

Test No.	4.1	4.2	4.3	4.4	4.7
Chemical analysis					
Combustible	19.2	22.5	5.4	3.8	5.2
Sulphur	4.8	5.6	8.4	8.8	3.6
CaO	44.2	32.0	29.8	25.6	17.1
MgO	1.6	18.2	17.5	13.7	7.2
Size grading	% within stated size grade				
- 6350 + 3175 μm	1	0	0	0	0
- 3175 + 1587 μm	51	23	10	14	14
- 1587 + 794 μm	30	57	35	36	35
- 794 + 500 μm	8	15	23	23	23
- 500 + 211 μm	8	4	15	13	15
- 211 + 152 μm	1	1	4	3	3
- 152 + 75 μm	1	0	8	7	6
- 75 + 0 μm	0	0	5	4	4

Analyses are stated as weight percent on an "as received" basis.

No bed material was removed during Tests 4.5, 4.6, 4.8 and 4.9

Table A3.35. Test Series 4 (100 h). Chemical analysis and size grading of cyclone fines

Test No.	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9
Chemical analysis									
Combustible	41.7	52.2	21.0	32.3	32.4	21.3	36.1	16.6	16.6
Sulphur	2.4	1.9	3.4	4.4	3.1	3.4	3.9	2.6	2.6
CaO	17.9	10.5	28.6	19.2	17.4	29.0	18.9	36.6	36.6
MgO	1.0	5.9	18.6	11.7	11.5	20.0	12.2	6.6	6.6
Size grading	% within stated size range								
-3175 + 1587 µm			0						
-1587 + 794 µm			1	0	0	0		0	0
- 794 + 500 µm	0	0	1	1	1	1	0	2	2
- 500 + 211 µm	13	8	6	7	9	5	7	5	5
- 211 + 152 µm	10	7	4	5	6	4	5	5	5
- 152 + 75 µm	20	23	24	22	22	23	23	28	28
- 75 + 0 µm	57	62	64	65	62	67	65	60	60

Analyses are stated as weight percent on an "as received" basis

Table A3.36. Test Series 4 (100 h). Performance data

Test No.		4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9
Elapsed time from start of test, h	Start	22	36	46	56	66	76	86	96	99
	End	26	40	50	60	70	80	90	99	101
Operating conditions										
Ca/S mol ratio		2.94	1.89	1.88	0.62	0.61	1.79	0.66	4.78	5.56
Acceptor Acceptor size (upper limit) µm		L	D	D	D	D	D	D	D	D
Recycle		Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No
Bed weight, lb		350	310	210	230	200	180	250	200	210
Unburnt carbon	%	>24	>8	>5	>0.4	>5	>5	>5	>7	>29
Excess air	%	-5.7	-5.7	-6.7	-8.9	-9.3	-12.0	-0.9	-11.0	4.4
Gas composition										
CO_2 % v/v		12.3	14.5	13.7	12.3	12.9	14.1	13.1	17.5	14.8
CO % v/v		0.64	0.60	0.72	0.74	0.75	0.69	0.63	0.75	0.64
O_2 % v/v		4.0	4.5	4.3	3.8	4.1	3.8	4.4	3.7	5.6
SO_2 ppm v/v		550	530	450	1160	1730	1060	650	750	370
NO_x ppm v/v		410	-	480	-	-	-	-	480	-
Bed Temp. °F										
Height above distributor plate										
3 in		1427	1411	1544	1562	1693	1697	1416	1663	1562
9 in		1427	1411	1544	1566	1693	1697	1420	1663	1566
15 in		1422	1413	1546	1573	1693	1695	1431	1663	1566
21 in		1436	1436	1504	1553	1634	1680	1438	1593	1503
Mean		1428	1418	1535	1564	1678	1680	1426	1645	1549

L denotes -3175 µm Limestone 18.

D denotes -1587 µm Dolomite 1337.

Table A3.37. Test Series 4 (100 h)

Mass Flows (lb/h)

Test No.	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9
Air Input									
Through distributor plate	1980	1980	1980	1970	1990	1970	1980	1980	1980
Coal conveying	220	220	220	220	220	220	220	225	225
External fines recycle	97	95	97	99	99	99	97	99	99
Total	2300	2300	2300	2280	2310	2290	2300	2310	2310
Coal Input	238	238	240	243	247	251	227	251	216
Acceptor Input	66	66	66	22	22	66	22	176	176
Bed extract	75	19	5	1	Nil	Nil	5	Nil	Nil
Cyclone fines rejected	69	19	44	2.5	28	41	22	78	280

Exhaust dust flow rates were not assessed.

Table A3.38. Test Series 4 (100 h)

Effect of Operating Conditions on Sulphur Retention

Test No.	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9
Acceptor	L	D	D	D	D	D	D	D	D
Ca/S mol ratio	2.94	1.89	1.88	0.62	0.61	1.79	0.66	4.78	5.56
Recycle	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No
Bed weight, lb	350	310	210	230	200	180	250	200	210
Bed Temp. °F	1428	1418	1535	1564	1678	1680	1426	1645	1549
Sulphur Retention %	78	78	82	54	31	58	72	69	82
SO_2 Reduction %	73	74	78	44	16	48	69	64	82

L denotes Limestone 18, sized -3175 micron,

D denotes Dolomite 1337, sized -1587 micron.

Table A3.39 Test Series 4

Effect of various parameters on sulphur retention

Variable Parameters i.e. Effect of	Constant Parameters		Sulphur Retention %	SO_2 Reduction %
	at	with		
Change in temperature 1488° to 1535°F and change in bed weight 310 to 210 lb	1.9 Ca/S mol ratio	-1587 μm Dolomite 8.2 ft/s and Recycle	change from 78 to 82	change from 74 to 78
Change in temperature from 1426° to 1564° to 1678°F	0.6 Ca/S mol ratio	-1587 μm Dolomite 8.2 ft/s Recycle and Bed wt. 210-250 lb.	change from 72 to 54 to 31	change from 69 to 44 to 16
Operation with -3175 μm Lime-stone at 2.9 Ca/S mol ratio OR Operation with -1587 μm Dolomite at 1.9 mol ratio	1420°F	Recycle. Bed weight 310-350 lb	Constant at 78	Constant at 74
Operation at 1.6 Ca/S mol ratio with recycle and Operation at 5.6 Ca/S mol ratio without recycle	1540°F	-1587 μm Dolomite 8.2 ft/s Bed weight 210 lb	Constant at 82	Constant at 80

Table A3.40. Mass Balance, Test 2.6

Operating conditions: Acceptor: -150 micron Limestone 18
Ca/S mol ratio: 3.55
Bed temperature: 1551°F
With external recycle of cyclone fines
Fluidising velocity: 8.1 ft/s

Data given in lb/h

Component	Total	Ash	C	O	N	S	Ca	Mg
INPUT								
Coal	227	30.4	159.7	12.2	2.5	6.88	1.54	0.30
Acceptor	65	41.2	6.5	17.3	0	-	21.33	0.55
Air	2270	0	0	527	1743	0	0	0
Total input	2562	72	166	567	1746	6.9	22.8	0.85
OUTPUT								
dry exit gas	2205	0	138.1	457	1768	2.04	0	0
water vapour	102	0	0	87.0	0	0	0	0
bed extract	5	4.5	0.1	0.2	-	0.14	0.52	0.06
cyclone fines	61	42.1	13.7	2.8	-	1.89	13.69	0.44
exhaust dust	33	22.4	4.3	3.2	-	2.11	8.49	0.22
Total output	2406	69	156	550	1768	6.2	22.7	0.72
Input-Output	154	3	10	17	-22	0.7	0.1	0.13
Difference %	6	4	6	3	-1	10	0	15

Table A3.41. Mass Balance, Test 2.7

Operating conditions: Acceptor: -150 micron Limestone 18

Ca/S mol ratio: 1.17

Bed temperature: 1554°F

With external recycle of cyclone fines

Fluidising velocity: 8.1 ft/s

Data given in lb/h

Component	Total	Ash	C	O	N	S	Ca	Mg
INPUT								
Coal	229	30.7	161.0	12.3	2.5	6.94	1.56	0.31
Acceptor	20	12.7	2.3	5.3	0	0	6.53	0.17
Air	2250	0	0	522.0	1730	0	0	0
Total input	2499	43	163	540	1733	6.9	8.1	0.5
OUTPUT								
dry exit gas	2218	0	141.1	468.3	1723	3.96	0	0
water vapour	103	0	0	87.8	0	0	0	0
bed extract	5	4.5	0.2	0.2	-	0.14	0.54	0.09
cyclone fines	39	27.0	9.3	1.6	-	1.09	5.89	0.14
exhaust dust	20	14.6	3.2	2.5	-	0.86	3.09	0.12
Total output	2385	46	154	560	1723	6.1	9.5	0.35
Input-output	114	-3	9	-20	10	0.8	-1.4	0.15
Difference %	5	-7	6	-4	1	12	-17	30

Table A3.42 Mass Balance, Test 2.9.2

Operating conditions: Acceptor: −150 micron Limestone 18
Ca/S mol ratio: 1.45
Bed temperature: 1545°F
Without external recycle of cyclone fines
Fluidising velocity: 8.1 ft/s

Data given in lb/h

Component	Total	Ash	C	O	N	S	Ca	Mg
INPUT								
Coal	176	19.4	127.7	9.8	2.0	5.5	0.99	0.19
Acceptor	33	20.9	3.3	8.8	0	0	10.76	0.30
Air	2260	0	0	524.3	1736	0	0	0
Total input	2469	40	131	543	1738	5.5	11.7	0.5
OUTPUT								
dry exit gas	2226	0	116.0	492.5	1731	2.34	0	0
water vapour	80	0	0	69.0	0	0	0	0
bed extract	3	2.8	0.02	0.1	-	0.07	0.27	0.04
cyclone fines	40	24	14.5	0.4	-	0.68	6.46	0.19
exhaust dust	6	4	0.5	0.8	-	0.51	1.51	0.04
Total output	2355	31	131	563	1731	3.6	8.2	0.3
Input-Output	114	9	0	-20	7	1.9	3.5	0.2
Difference %	5	23	0	-4	0	35	30	40

Table A3.43. Mass Balance Test 3.6

Operating conditions: Acceptor: -150 micron Limestone 18
Ca/S mol ratio: 2.66
Bed temperature: 1563°F
With external recycle of cyclone fines
Fluidising velocity: 6.4 ft/s

Data given in lb/h

Component	Total	Ash	C	O	N	S	Ca	Mg
INPUT								
Coal	185	21.3	134.8	9.5	2.1	5.4	1.08	0.21
Acceptor	56	35.5	5.6	14.9	0	0	18.29	0.47
Air	1780	0	0	413.0	1367	0	0	0
Total input	2021	57	140	437	1369	5.4	19.4	0.68
OUTPUT								
dry exit gas	1733	0	111.5	361.6	1386.3	0.65	-	-
water vapour	85	0	0	73.3	0	0	0	0
bed extract	2.4	2.1	0.06	0.1	-	0.08	0.29	0.05
cyclone fines	65	45.6	15.5	0.6	-	1.56	15.33	0.27
exhaust dust	21	15.2	2.6	1.8	-	1.37	7.17	0.43
Total output	1906	63	130	437	1386	3.7	22.8	0.75
Input-output	115	-6	10	0	-17	1.7	-3.4	-0.07
Difference %	6	-11	7	0	-1	31	-18	-10

Table A3.44. Mass Balance, Test 3.7

Operating conditions: Acceptor: -1587 micron Dolomite 1337
Ca/S mol ratio: 1.74
Bed temperature: 1549°F
Fluidising velocity: 8.2 ft/s
With external recycle of cyclone fines

Data given in lb/h

Component	Total	Ash	C	O	N	S	Ca	Mg
INPUT								
Coal	229	28.2	165.3	11.7	2.5	6.64	1.43	0.28
Acceptor	69	37.4	8.6	23.0	0	0	14.50	8.91
Air	2280	0	0	529.0	1721	0	0	0
Total input	2578	66	174	564	1724	6.6	15.9	9.2
OUTPUT								
dry exit gas	2241	0	139.3	475	1753.2	1.59	0	0
water vapour	104	0	0	89.8	0	0	0	0
bed extract	13	10.2	0.6	1.3	-	0.88	2.52	0.05
cyclone fines	82	52.0	22.3	3.7	-	3.20	15.24	8.45
exhaust dust	13	10.2	2.3	0.5	-	0.33	0.97	0.43
Total output	2453	72	165	570	1753	6.0	18.7	8.9
Input—output	125	-6	9	-6	-29	0.6	-2.8	0.3
Difference %	5	-9	5	-1	-2	10	-18	3

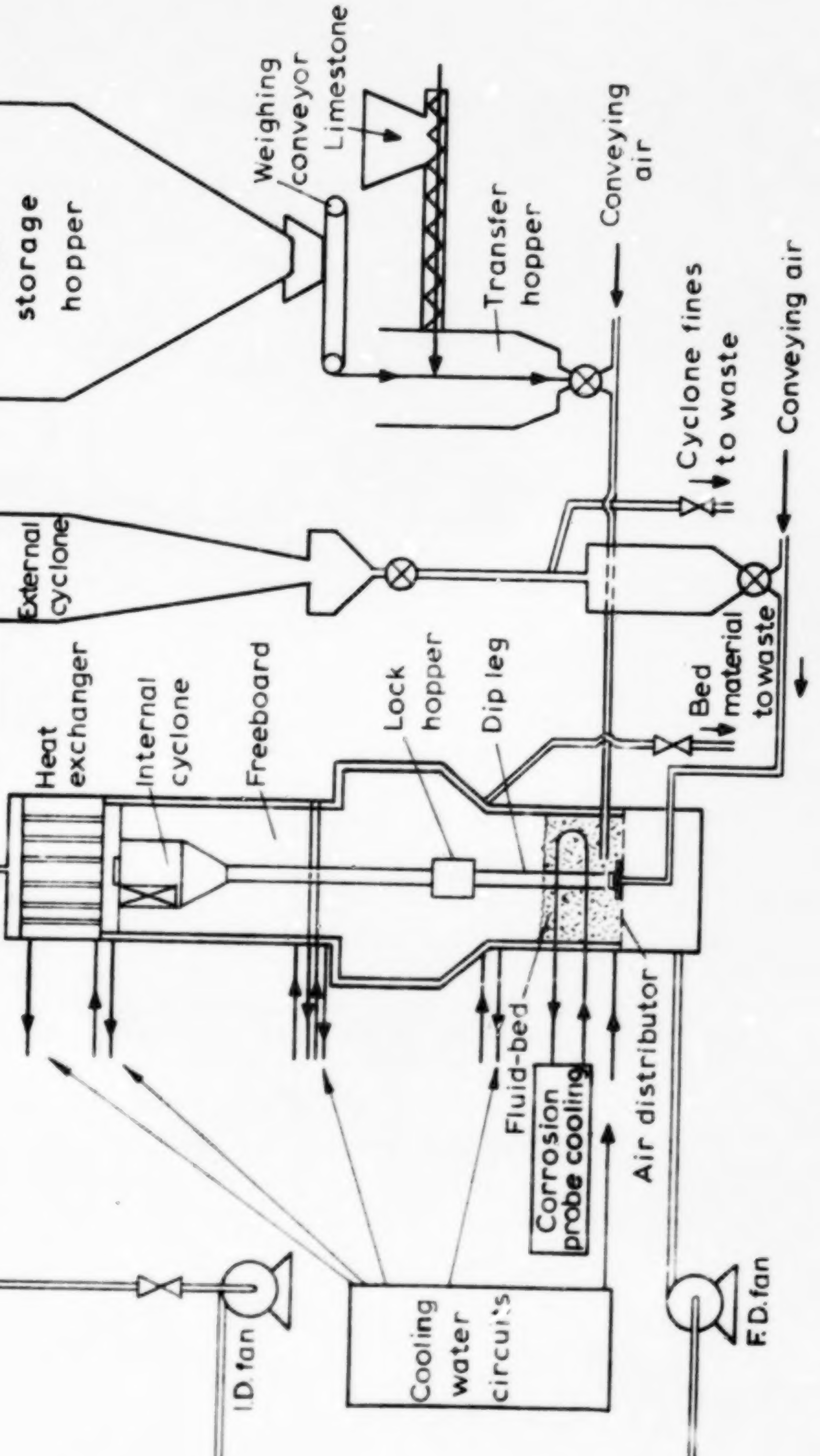


Fig. A3.1. Flow diagram of 27in combustor

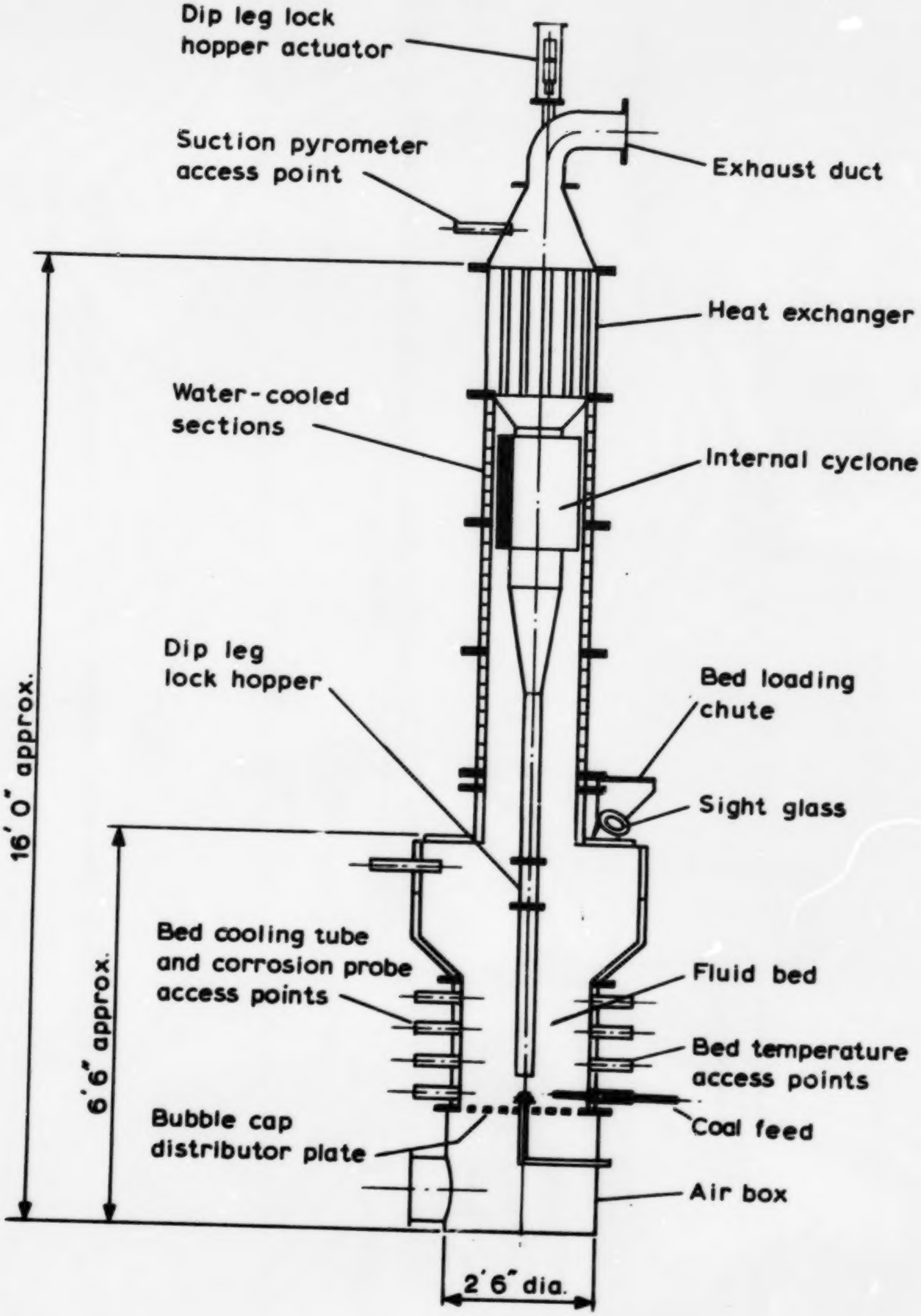


Fig A3.2. The 27in combustor

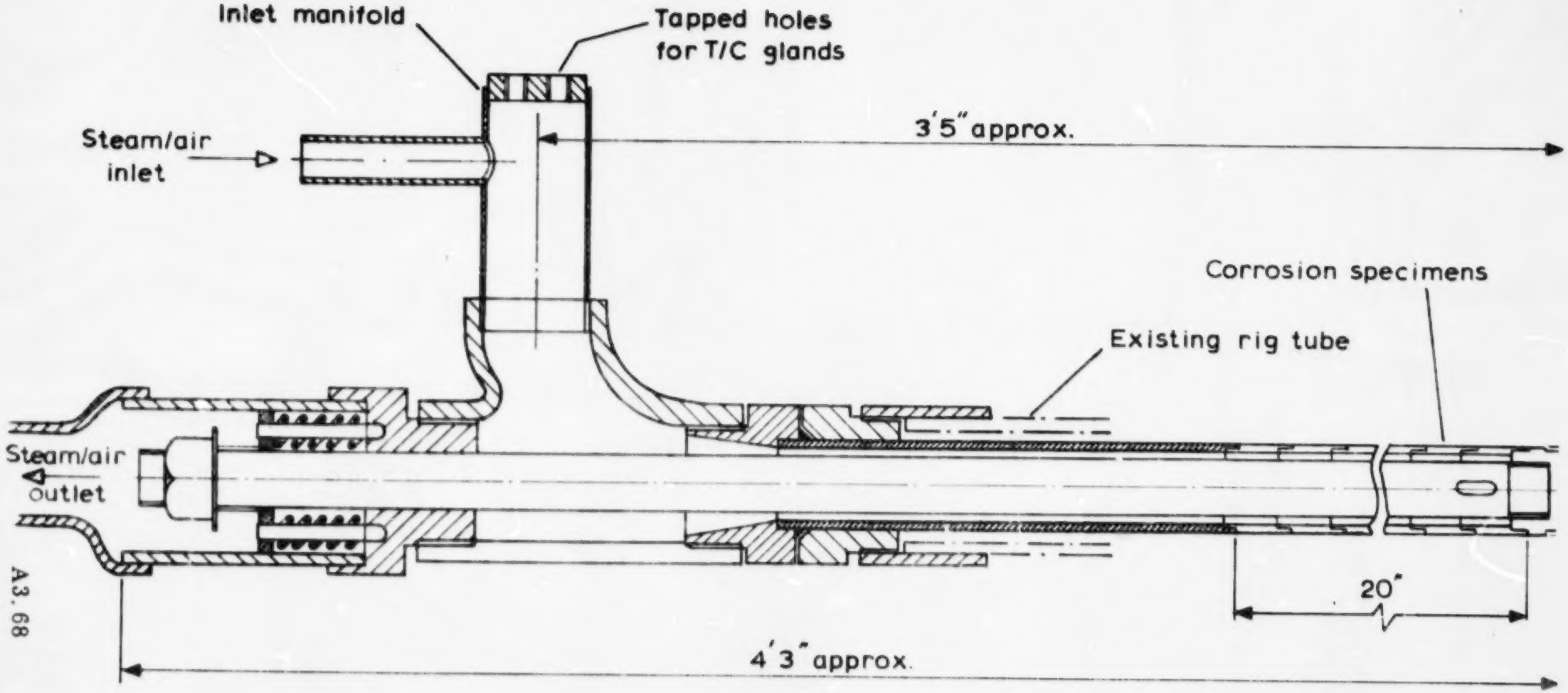
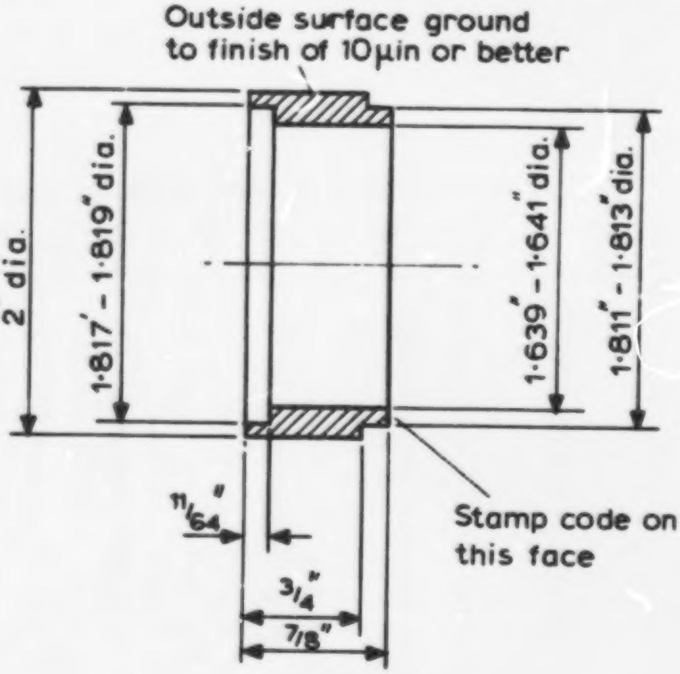
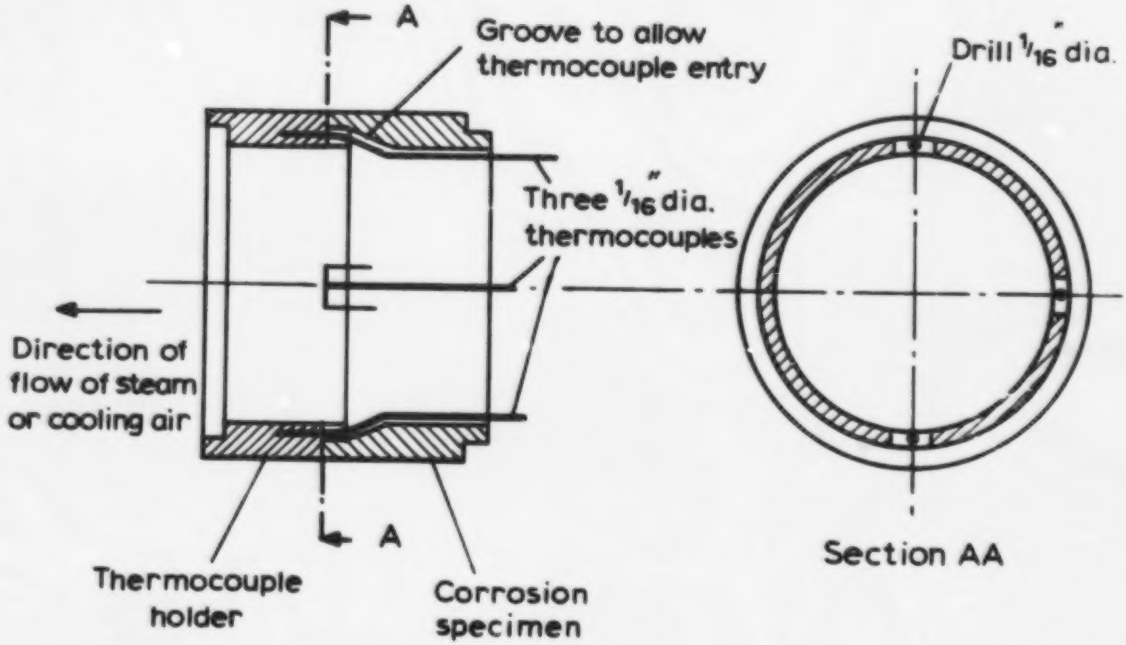


Fig A3.3. General arrangement - corrosion probe



All corners to have 0·005" rad.

Section through corrosion specimen


A
A
Groove to allow thermocouple entry
Drill 1/16" dia.
Three 1/16" dia. thermocouples
Direction of flow of steam or cooling air
Thermocouple holder
Corrosion specimen
Section AA

Arrangement of thermocouples in corrosion specimen

Fig. A3. 4. Details of corrosion specimens

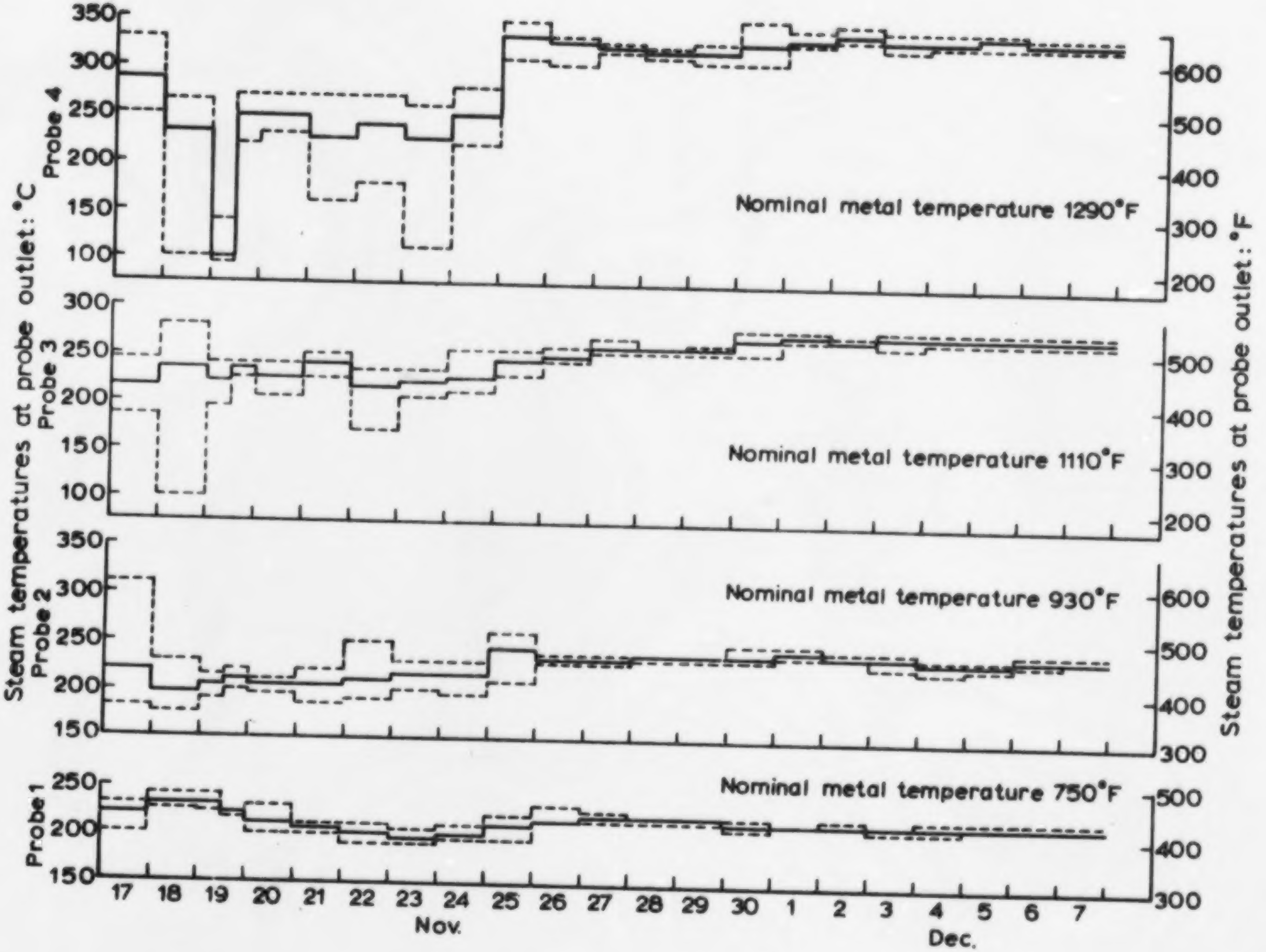


Fig. A3. 5. Test Series 1b. (500h). Variation in steam temperature at outlets of corrosion probes

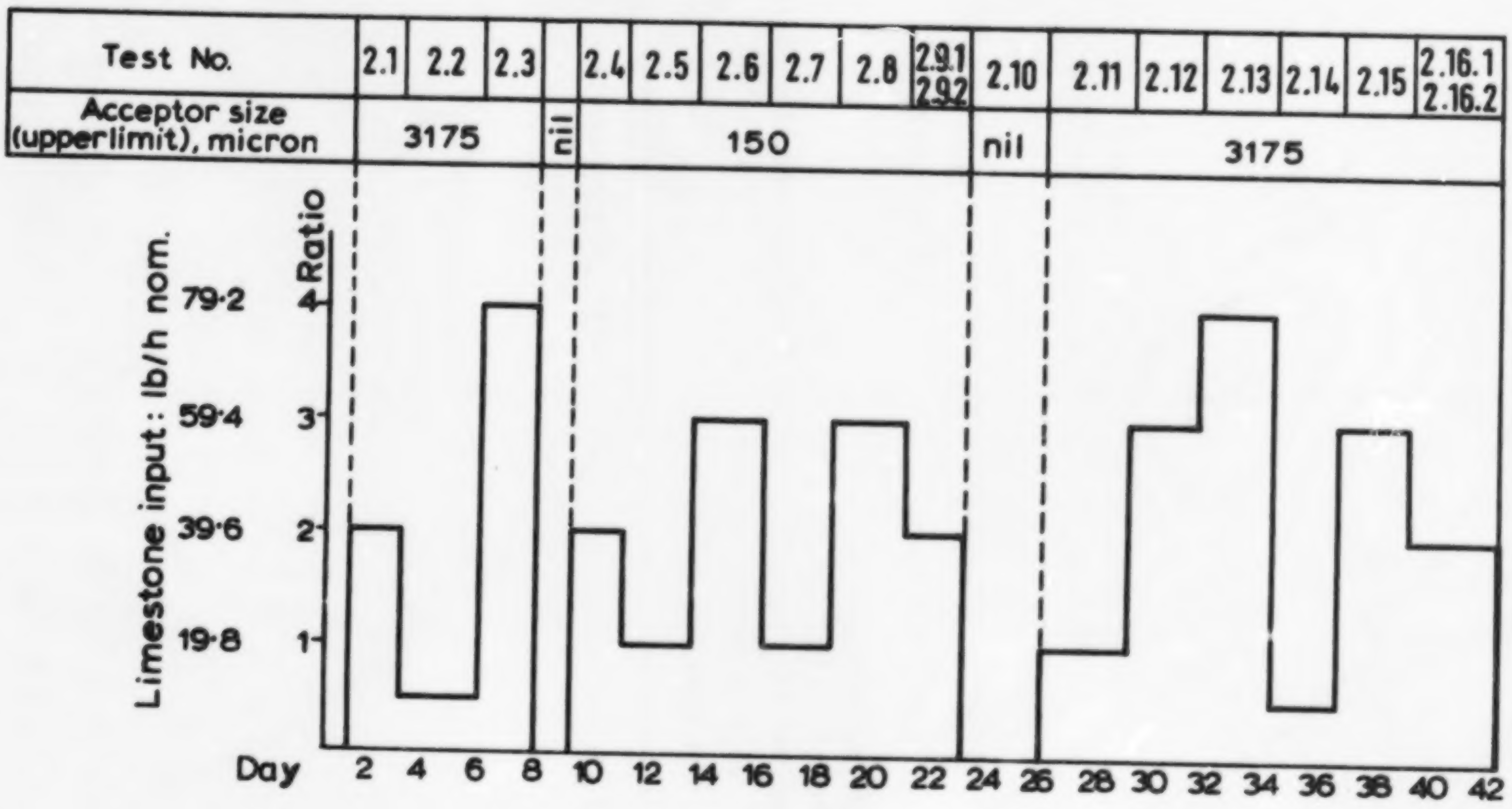
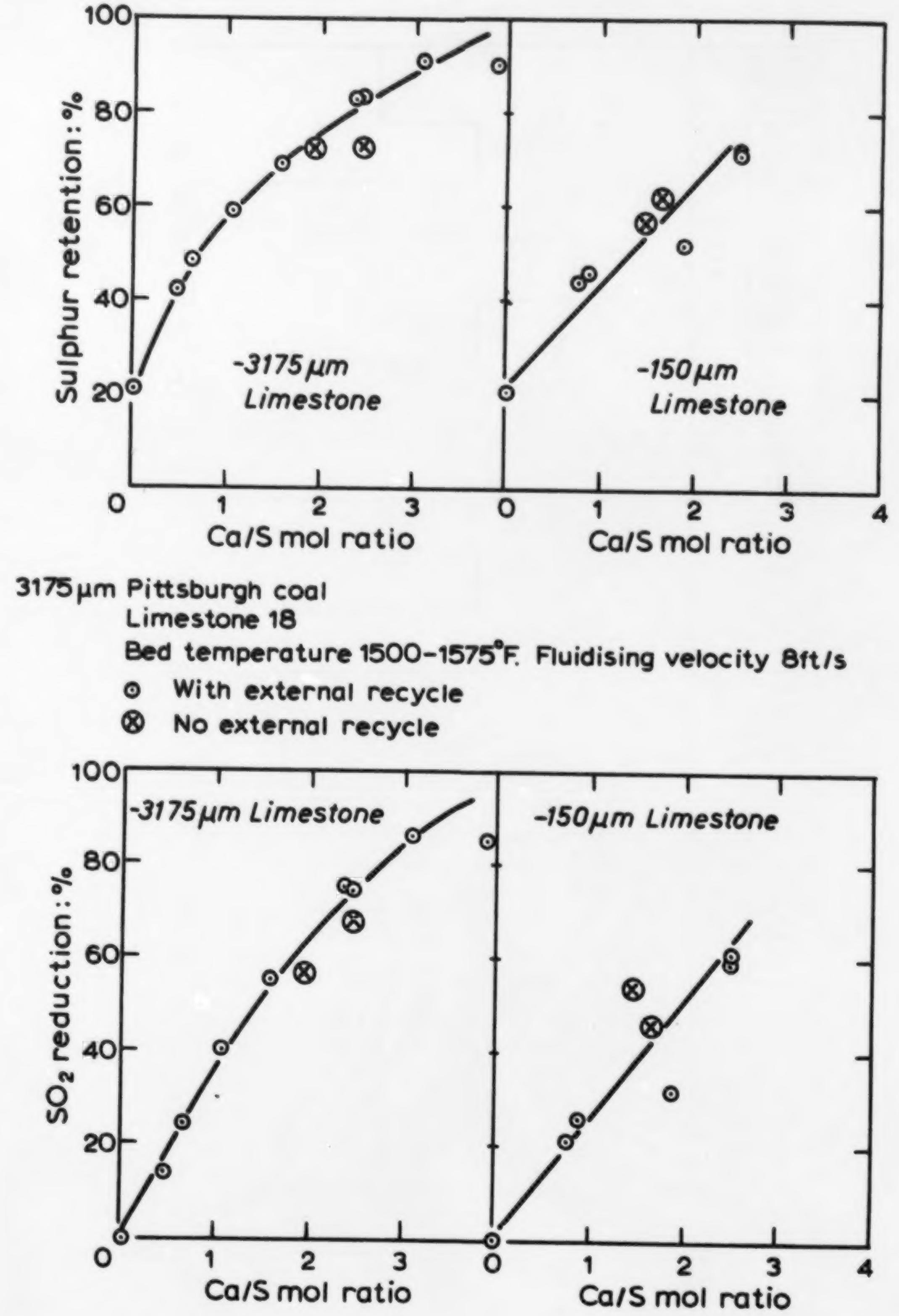
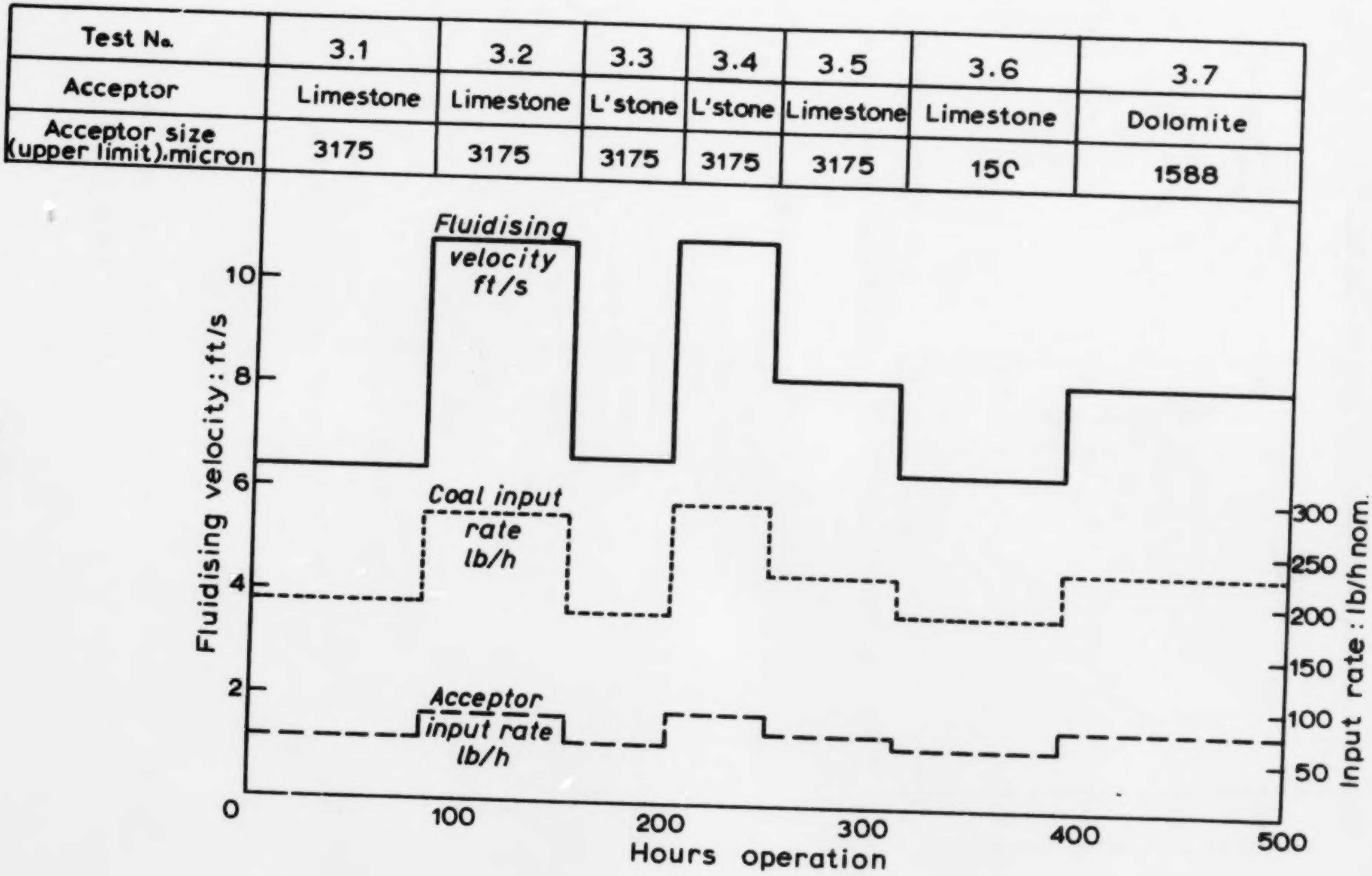


Fig. A3.6. Test Series 2. Test schedule



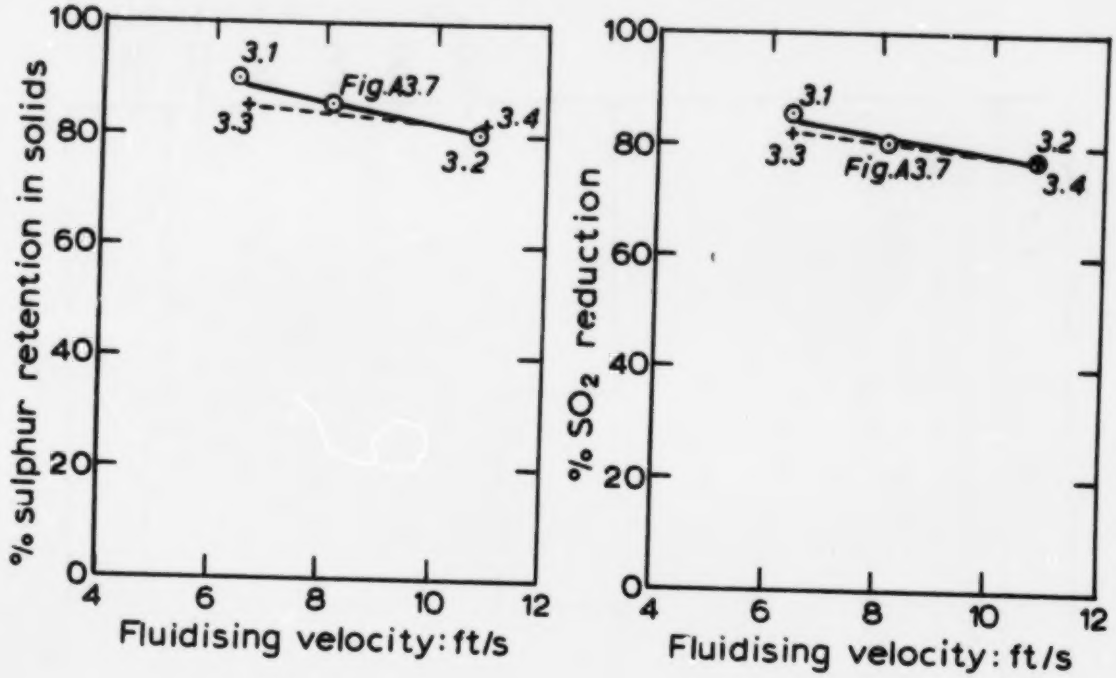
3175µm Pittsburgh coal
Limestone 18
Bed temperature 1500–1575°F. Fluidising velocity 8ft/s
⊙ With external recycle
⊗ No external recycle

Fig. A3.7. Test Series 2. Effect of Ca/S mol ratio on sulphur retention and SO_2 reduction



Test No.	3.1	3.2	3.3	3.4	3.5	3.6	3.7
Acceptor	Limestone	Limestone	L'stone	L'stone	Limestone	Limestone	Dolomite
Acceptor size (upper limit), micron	3175	3175	3175	3175	3175	150	1588

Fig. A3. 8. Test Series 3. Test schedule



Acceptor: −3175μm Limestone 18
Ca/S mol ratio: 2·7
Bed temperature: 1550°F

Test No.	Bed weight: lb	Recycle
3.1	220	Yes
3.2	210	Yes
3.3	220	No
3.4	260	No

Numbers adjacent points are test nos.
o With recycle
x No recycle

Fig. A3.9. Test Series 3. Effect of fluidising velocity on sulphur retention and SO_2 reduction

Test No.	1	2	3	4	5	6	7	8	9
Acceptor	Limestone	Dolomite	Dol.	Dol.	Dol.	Dol.	Dol.	Dol.	Dol.
Temperature: °F	1420	1420	1560	1560	1700	1700	1420	1700	1560

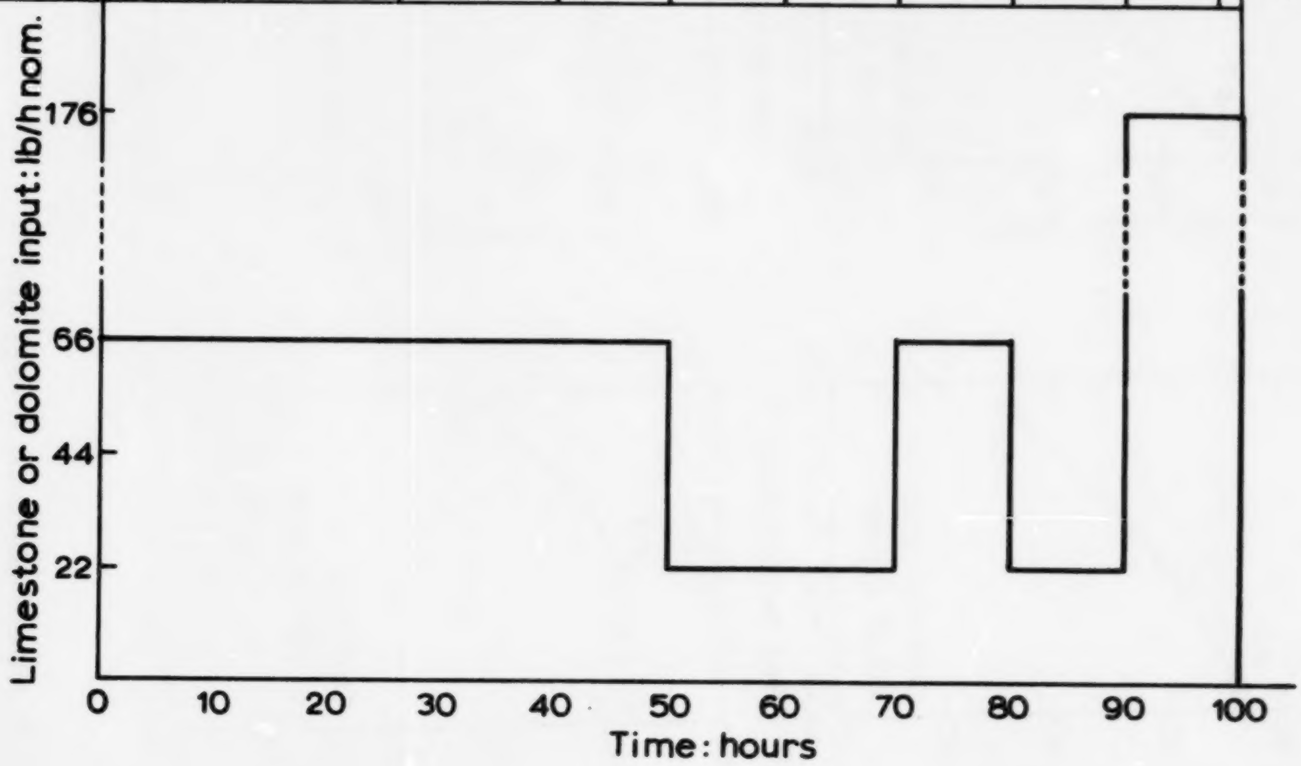
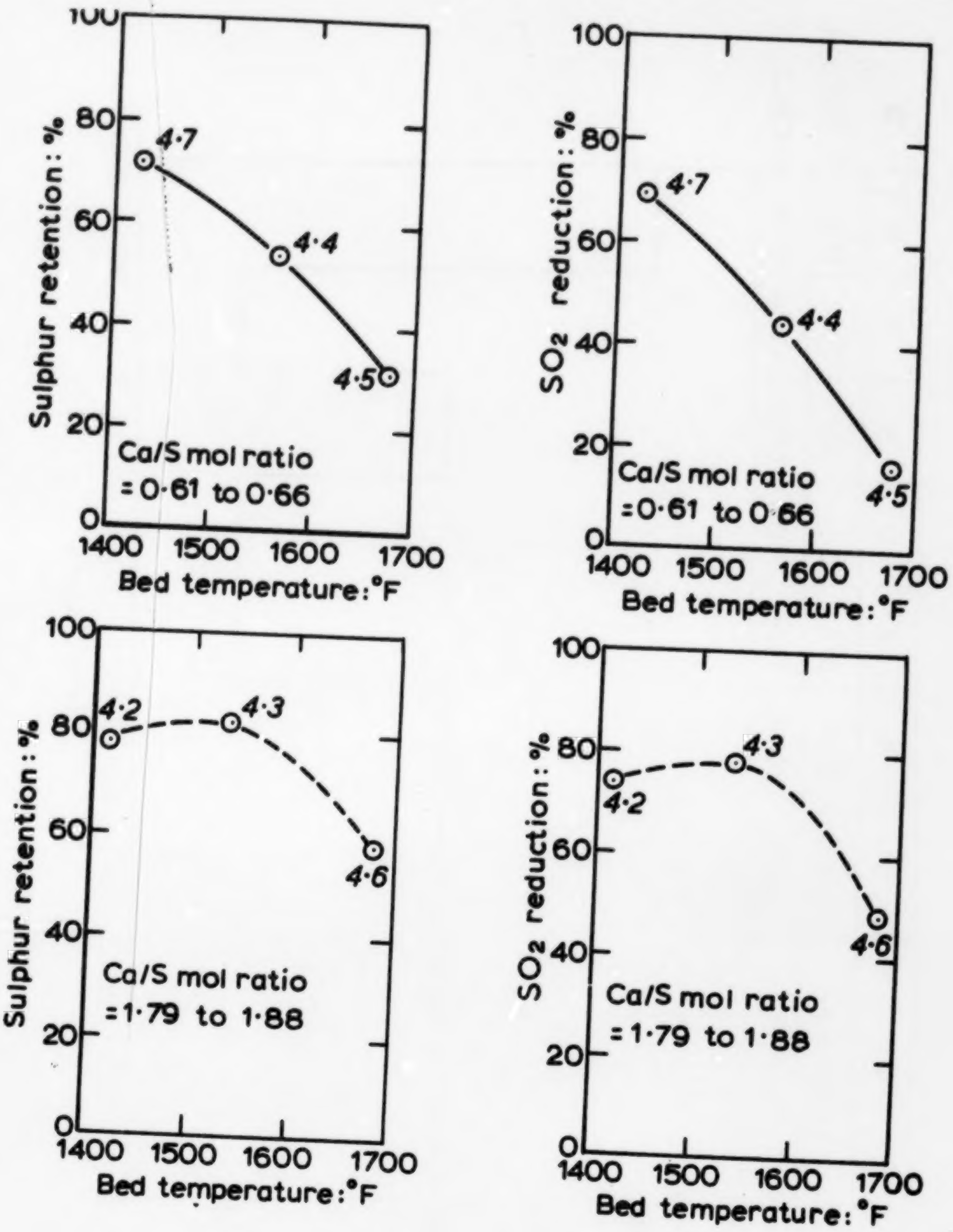


Fig. A3.10. Test Series 4. Test schedule



Numbers adjacent points are Test numbers
Acceptor: −1587 μm Dolomite
Fluidising velocity: 8 ft/s
Operation with recycle

Fig. A3.11. Test Series 4. Effect of bed temperature on sulphur retention and SO_2 reduction